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Control of Waste and Water Pollution from Coal-Fired Power Plants: Second R and D Report

Aerospace Corp, El Segundo, CA

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Industrial Environmental Research Lab, Research Triangle Park, NC

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Coal	Desulfurization	Flue Gas Cleaning	21D	07A,07D
Combustion	Water Reclamation	Coal Piles	21B	
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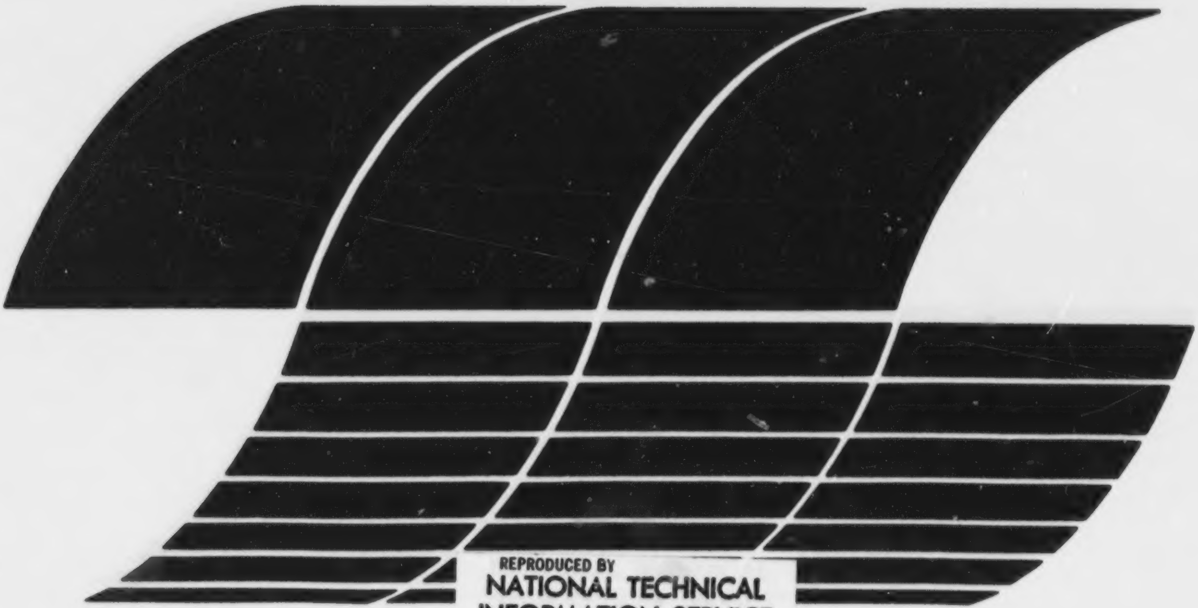

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November 1978

Control of Waste and Water Pollution from Coal-fired Power Plants:
Second R&D Report

by

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Program Element No. EHE624A

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ABSTRACT

This is the second annual report of a series summarizing and assessing the state of research and development in the fields of nonregenerable flue gas cleaning waste treatment, utilization, and disposal, as well as water reuse technology for coal-fired utility power plants. It is based upon information available through November 1976.

Significant results cover the following areas: coal-pile drainage, ash characterization and disposal, chemical and physical properties and leaching characteristics of treated and untreated wastes, field evaluations of treated and untreated waste disposal, assessment of alternatives for the disposal of scrubber wastes in coal mines and the ocean, physical and chemical properties of gypsum produced from flue gas desulfurization systems, cost estimates for producing and disposing of gypsum, flue gas desulfurization potential use of wastes in fertilizer production, and the economics of alumina production and total power plant water reuse.

Future reports that are to be issued annually will continue to evaluate the progress of flue gas cleaning waste disposal and utilization technology. Results not available, but to be included in subsequent reports, will cover the areas of soil attenuation effects, and conceptualized design cost analyses for various methods of flue gas cleaning waste disposal, gypsum production, and marketing and assessment of processes for potential use of wastes in portland cement manufacture and production of sulfur or sulfuric acid.

ACKNOWLEDGMENTS

This report, prepared by The Aerospace Corporation, is the result of a continuing cooperative effort of many individuals and organizations, all of whom have made significant contributions to the projects being reported. The authors wish to acknowledge Julian W. Jones, U.S. Environmental Protection Agency Project Officer, for his guidance and continued assistance in conducting this study and in providing timely access to data necessary for the preparation of this report.

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CONVERSION TABLE

British	Metric
1 inch	2.54 centimeters
1 foot	0.3048 meter
1 mile	1.609 kilometers
1 square foot	9,290 square centimeters
1 acre	4,047 square meters
1 cubic foot	28,316 cubic centimeters
1 gallon	3.785 liters
1 cubic yard	0.7646 cubic meter
1 pound	0.454 kilogram
1 ton (short)	0.9072 metric ton
1 pound per square inch	0.0703 kilogram per square centimeter
1 pound per cubic foot	0.01602 gram per cubic centimeter
1 ton per square foot	9,765 kilograms per square meter
1 part per million	1 milligram per liter (equivalent)
1 British thermal unit (Btu)	252 calories
1 pound per million Btu	0.43 grams per million joules; 1.80 grams per million calories
1 Btu per pound	2.324 joules per gram; 0.555 calories per gram

SECTION I

INTRODUCTION

1.1 BACKGROUND

A major consideration in controlling pollutants from modern coal-fired, steam-electric generating plants is the environmental management of solid wastes and effluents. Essentially, all the solid wastes, excluding bottom ash, are generated as a result of air pollution devices to control sulfur dioxide and fly ash emissions. The solid wastes, in turn, present their own potential water pollution problems once they are removed from the control devices for disposal.

The environmental legislation of the past several years provides the framework for regulation of these effluents and wastes, and the development of technology to minimize their adverse environmental impacts has, in a number of cases, required significant research and development efforts. The need for these efforts was the basis for the formulation of the programs described in this report.

A significant portion of the efforts in this area is currently being funded by the U.S. Environmental Protection Agency (EPA). Twenty-one different EPA projects are either completed or are under way. Work has also been and is being conducted by utilities and other industrial organizations involved in the treatment and disposal process. In addition, full-scale systems are currently in operation, and others are in various stages of planning and implementation.

1.2 SCOPE

The Aerospace Corporation under Task 9 of EPA Contract No. 68-02-1010 has been contracted to integrate and evaluate the research and development (R&D) work being performed in the area of power plant waste disposal and utilization, as well as overall power plant water recycle and reuse. This report is the second in a series and provides an updated evaluation of the R&D results of the EPA-funded projects, as well as information available since the first report, on work being performed by other domestic

(U.S.) and foreign organizations. The assessment of the results and technology is related to the definition of environmentally sound and economic disposal of or utilization of FGD wastes and water recycle, reuse, and treatment. In addition, a summary of the status of full-scale operational FGD waste disposal systems is reported.

1.2.1 The EPA Program

In late 1974, plans were formulated to greatly expand existing EPA flue gas desulfurization (FGD) waste disposal R&D efforts. These efforts were aimed at determining pertinent environmental parameters, reducing costs, investigating alternative strategies, and encouraging waste-product usage. Although the major emphasis was on FGD wastes, the plans involved consideration of overall power plant waste and water problems, including the disposal and utilization of coal ash. The program is currently entitled "Control of Waste and Water Pollution from Coal-Fired Power Plants" or, for brevity, "Waste and Water Program."

The objectives of the Waste and Water Program are to evaluate, develop, demonstrate, and recommend environmentally acceptable cost-effective techniques for disposal and utilization of flue gas cleaning (FGC) wastes and to evaluate and demonstrate systems for maximizing power plant water recycling and reuse. The projects, in general, fall into one of six main categories: (1) environmental assessment of FGC waste disposal, (2) technology assessment development, (3) disposal economics, (4) alternative disposal methods, (5) utilization of wastes, and (6) power plant water recycle and treatment for reuse.

The environmental assessment projects include FGC waste characterization studies; laboratory and pilot field studies of disposal techniques for chemically treated FGD sludges; characterization of coal-pile drainage, coal ash, and other power plant effluents; and studies of attenuation of FGC waste leachate by soils. Chemical and physical properties have been determined by several laboratories for untreated FGC wastes from a total of 13 scrubbers, wastes treated by 5 distinct processes, and gypsum produced in an EPA laboratory pilot plant facility.

The technology assessment and development efforts include field studies of untreated and chemically treated FGD wastes, FGC waste leachate-disposal site liner compatibility studies, studies to correlate waste solid characteristics with scrubber operating conditions, and dewatering equipment design studies. The economic studies include cost estimates of current disposal practices (e.g., ponding, landfill) and by-product marketing studies. Alternative disposal method studies include both mine and ocean disposal assessments. Utilization projects include development of a process for FGC waste conversion (to sulfur and calcium carbonate), pilot studies of fertilizer production (using the waste as a filler material and a source of sulfur), use of FGD gypsum in portland cement manufacture, and FGC waste beneficiation studies. Studies to define methods of minimizing water consumption by electric utility power plants by recycling and reuse of water from FGC processes and major water-use systems are being conducted, as well as methods of treating purge streams.

Table 1 shows the relationship of each of the projects to the areas of interest. Whereas four of the projects are aimed at investigating one specific area, the others cover several areas of interest. This is to be expected, since it would be difficult, for example, to fairly assess the technology of a process without examining both the economics and the environmental effects. An overview of the EPA program as it relates to the various elements of the FGC solid waste and liquid effluent generation, treatment, disposal, and utilization is shown in Figure 1. The projects and contractors are identified and keyed to the elements of the system addressed.

In Section V, each of the projects is discussed, and the current project status and results are described. These are listed under the heading of the main area of interest. Table 2 identifies the EPA project officer, contractor project director, start date, and duration of each of the projects, as well as the section in which each of these projects is discussed.

1.2.2 Other Programs

Other organizations including utilities and FGD waste fixation contractors have conducted work on various aspects of the overall disposal problem that are generally of a site-specific nature. The results of work conducted by United States industrial organizations are discussed in Section VII, and the status of full-scale operational FGD waste disposal system is also provided in that section. Section VI provides information on university-related work, and foreign technology is discussed in Section VIII.

1.3 TECHNICAL BASIS FOR THIS REPORT

This report is based generally on published information available through November 1976 and subsequent to December 1975, which was the cutoff date for the first R&D report (Ref. 1). During its preparation, information developed from informal contacts was included, as appropriate. Annual updating of this report is planned by the EPA.

TABLE 1. RELATIONSHIP OF PROJECTS IN FGC WASTE AND WATER PROGRAM TO AREAS OF INTEREST

Project	Contractor	Environmental Assessment	Technology Assessment and Development	Economic Studies	Alternative Disposal Methods	Utilization Methods Development	Overall Power Plant Water Use
FGC Waste Characterization and Disposal Evaluation	Aerospace[b]	X	X	X	X		
Shawnee FGD Waste Disposal Field Evaluation	TVA[c] and Aerospace[b]	X	X	X	X		
Laboratory and Field Evaluation of FGC Treatment Processes	U.S. Army WES[d]	X	X				
Characterization of Effluents from Coal-Fired Power Plants	TVA[e]	X					
Fly Ash Characterization and Disposal	TVA[e]	X	X	X			X
Attenuation of FGC Waste Leachate by Soils	U.S. Army, Dugway[f]	X					
Establishment of Data Base for FGC Disposal Standards	SCS[g]	X	X				
Environmental Effects and Control of Various FGC Sludge Disposal Options	SCS[g]	X	X	X			
Evaluation of FGD Waste Disposal Options	LG&E[h]	X	X		X		
FGD Waste Leachate - Liner Compatibility	U.S. Army, WES[d]		X	X			
Scrubber Waste Characterization	TVA[e]		X				
Dewatering Principles and Equipment Design	Auburn U[i]		X				
Conceptual Design-Cost Studies of Alternative Methods for FGC Waste Disposal	TVA[j]		X	X			
Gypsum By-Product Marketing Studies	TVA[j]		X	X		X	

(Continued)

TABLE 1. RELATIONSHIP OF PROJECTS IN FGC WASTE AND WATER PROGRAM TO AREAS OF INTEREST (Continued)

Project	Contractor	Environmental Assessment	Technology Assessment and Development	Economic Studies	Alternative Disposal Methods	Utilization Methods Development	Overall Power Plant Water Use
Evaluation of Alternative FGC Waste Disposal Sites	A. D. Little[k]	X	X	X	X		
Scrubbing Waste Conversion Studies	Pullman Kellogg [l]		X	X		X	
Fertilizer Production Using Scrubbing Wastes	TVA[j]		X	X		X	
FGD Waste and Fly Ash Beneficiation	TRW[m]			X		X	
Assessment of Power Plant Water Recycle and Reuse	Radian[n]			X			X
Treatment of FGC Waste Streams by Vapor Compression Cycle Evaporation	RCC[o]						X
Power Plant Cooling Tower Blowdown Recycle by Vertical Tube Evaporator with Interface Enhancement	U. of California						X

[a] Primary area of interest is indicated by shaded areas.

[b] The Aerospace Corporation, El Segundo, California.

[c] Tennessee Valley Authority (TVA), Division of Chemical Development, Muscle Shoals, Alabama.

[d] U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

[e] TVA, Power Research Staff, Chattanooga, Tennessee.

[f] U.S. Army Materiel Command, Dugway Proving Ground, Utah.

[g] SCS Engineers, Long Beach, California.

[h] Louisville Gas and Electric Company (LG&E), Louisville, Kentucky.

[i] Auburn University, Auburn, Alabama.

[j] TVA, Office of Agricultural and Chemical Development (OACD), Muscle Shoals, Alabama.

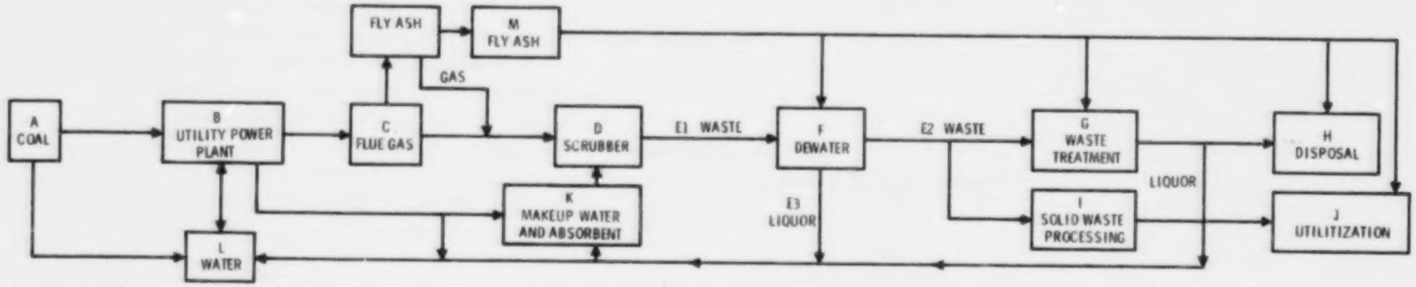
[k] Arthur D. Little, Inc., Cambridge, Massachusetts.

[l] Pullman Kellogg Company, Houston, Texas.

[m] TRW Systems Group, Redondo Beach, California.

[n] Radian, Inc., Austin, Texas.

[o] Resources Conservation Company, Renton, Washington.


FLY ASH
M FLY ASH
GAS
A COAL
B UTILITY POWER PLANT
C FLUE GAS
D SCRUBBER
E1 WASTE
F DEWATER
E2 WASTE
G WASTE TREATMENT
H DISPOSAL
K MAKEUP WATER AND ABSORBENT
E3 LIQUOR
I SOLID WASTE PROCESSING
LIQUOR
J UTILITIZATION
L WATER

- CHARACTERIZATION OF EFFLUENTS FROM COAL-FIRED POWER PLANTS (TVA), A, C, L

- FLY ASH CHARACTERIZATION AND DISPOSAL (TVA) C, M, H
- ASSESS AND DEMONSTRATE POWER PLANT WATER REUSE/RECYCLE (Radian) L, B, K
- EVALUATE USE OF VAPOR COMPRESSION EVAPORATOR TO REDUCE WATER POLLUTION FROM FGD PROCESSES (RCC), L
- RENOVATE COOLING TOWER BLOWDOWN BY VERTICAL TUBE EVAPORATOR (U of California), L

- LIME AND LIMESTONE SCRUBBING WASTE CHARACTERIZATION (TVA) D, $E_{1, 2, 3}$

- FGC WASTE CHARACTERIZATION AND DISPOSAL EVALUATION (Aerospace) $E_{1, 2, 3}$G, H, K, L, M
- DEWATERING PRINCIPLES AND EQUIPMENT DESIGN STUDIES (Auburn U) F

- LABORATORY AND FIELD EVALUATION OF FGC TREATMENT PROCESSES (U. S. Army WES) G, E_2, H
- EVALUATION OF FGC WASTE DISPOSAL OPTIONS (LG&E) G, H
- CONCEPTUAL DESIGN AND COST STUDIES OF ALTERNATIVE METHODS FOR LIME AND LIMESTONE SCRUBBING WASTE DISPOSAL (TVA) G, H
- LIME AND LIMESTONE SCRUBBING WASTE CONVERSION PILOT STUDIES (Pullman-Kellogg)
- FERTILIZER PRODUCTION USING LIME AND LIMESTONE SCRUBBING WASTES (TVA) I, J

- SHAWNEE FGD WASTE DISPOSAL FIELD EVALUATION (TVA and Aerospace) H, G, E_2
- ATTENUATION OF FGC WASTE LEACHATE BY SOILS (U. S. Army, Dugway) H
- ESTABLISHMENT OF DATA BASE FOR FGC WASTE DISPOSAL STANDARDS DEVELOPMENT (SCS Engr) H
- ALTERNATIVE DISPOSAL METHODS DEVELOPMENT (A. D. Little) H, $E_{1, 2}$, G
- FGC WASTE LEACHATE-LINER COMPATIBILITY (U. S. Army WES) H
- FGD WASTE AND FLYASH BENEFICIATION STUDIES (TRW) J, I
- GYPSUM BY-PRODUCT MARKETING STUDIES (TVA) J
- ENVIRONMENTAL EFFECTS AND CONTROL OF VARIOUS FGC SLUDGE DISPOSAL OPTIONS (SCS Engr) H, E_1, G

Figure 1. EPA program overview: control of waste and water pollution from FGC systems.

TABLE 2. PROJECT STATUS

Project Title	EPA Project Officer[a]	Contractor Project Director	Start Date	Estimated Duration, months	Type of Study	Section Referenced in This Report
Environmental Assessment of FGC Waste Disposal						5.1
FGC Waste Characterization, Disposal Evaluation, and Technology Transfer	J. W. Jones Industrial Environmental Research Laboratory (IERL) Research Triangle Park, NC	J. Rossoff The Aerospace Corporation El Segundo, CA	Nov 1972	50	Laboratory analyses: technical and economic	5.1.1
Shawnee FGD Waste Disposal Field Evaluation	M. C. Osborne[b] IERL Research Triangle Park, NC	A. F. Little TVA, Division of Chemical Development Muscle Shoals, AL J. Rossoff The Aerospace Corporation El Segundo, CA	Sep 1974	34	Field evaluation	5.1.2
Laboratory and Field Evaluation of FGC Waste Treatment Processes	R. E. Landreth Municipal Environmental Research Laboratory (MERL) Cincinnati, OH	P. G. Malone U.S. Army Engineer Waterways Experiment Station (WES) Vicksburg, MS				5.1.3
1. Pollution Potential of Untreated and Chemically Fixed Sludges			1. Jul 1974	1. 36	1. Laboratory	5.1.3.1
2. Site Survey and Environmental Assessment of Existing Solid Waste Disposal Sites			2. Jul 1975	2. 24	2. Laboratory, field	5.1.3.2
3. Evaluation of Existing Fixation Technology			3. Jul 1975	3. 26	3. Laboratory	5.1.3.3
Characterization of Effluents from Coal-Fired Power Plants	M. C. Osborne[b] R. A. Venezia IERL Research Triangle Park, NC	H. B. Flora TVA Power Research Staff Chattanooga, TN	Apr 1975	50	Laboratory, field	5.1.4
Fly Ash Characterization and Disposal	M. C. Osborne[b] R. A. Venezia IERL Research Triangle Park, NC	H. B. Flora TVA, Power Research Staff Chattanooga, TN	Apr 1975	42	Laboratory, field	5.1.5
Studies of Attenuation of FGC Waste Leachate by Soils	M. Roulier MERL Cincinnati, OH	M. Houle U.S. Army Materiel Command Dugway Proving Ground Dugway, UT	Dec 1975	24	Laboratory	5.1.6

(Continued)

TABLE 2. PROJECT STATUS (Continued)

Project Title	EPA Project Officer	Contractor Project Director	Start Date	Estimated Duration, months	Type of Study	Section
Establishment of a Data Base for FGC Waste Disposal Standards Development	D. E. Sanning MERL Cincinnati, OH	C. J. Schmidt SCS Engineers Long Beach, CA	Dec 1975	15	Technical analysis	5.1.7
Environmental Effects and Control of Various FGC Sludge Disposal Options	D. E. Sanning MERL Cincinnati, OH	C. J. Schmidt SCS Engineers Long Beach, CA	Sep 1976	24	Technical analysis	5.1.8
Process Technology Assessment and New Technology Development						5.2
Evaluation of FGD Waste Disposal Options	M. C. Osborne IERL Research Triangle Park, NC	R. P. Van Ness Louisville Gas and Electric Co. Louisville, KY	May 1976	18	Laboratory, field	5.2.1
FGD Waste Leachate-Liner Compatibility	R. E. Landreth MERL Cincinnati, OH	Z. B. Fry U.S. Army WES Vicksburg, MS	Jul 1975	30	Laboratory	5.2.2
Lime and Limestone Wet Scrubbing Waste Characterization	M. C. Osborne IERL Research Triangle Park, NC	J. L. Crowe TVA Energy Research Chattanooga, TN	Mar 1975[b]	28	Laboratory, field	5.2.3
Dewatering Principles and Equipment Design Studies	J. W. Jones IERL Research Triangle Park, NC	J. C. Warman Auburn University Auburn, AL	June 1976	27	Laboratory	5.2.4
Process Economics Studies						5.3
Conceptual Design and Cost Studies of Alternative Methods for Lime and Limestone Scrubbing Waste Disposal	J. W. Jones[a] IERL Research Triangle Park, NC	H. L. Faucett TVA, Office of Agricultural and Chemical Development (OACD) Muscle Shoals, AL	Jan 1976	18	Technical and economic analyses	5.3.1
Gypsum By-Product Marketing Studies	J. W. Jones IERL Research Triangle Park, NC	J. I. Bucy TVA, OACD Muscle Shoals, AL	Jan 1976	12	Technical and economic an analyses	5.3.2
Alternative FGC Waste Disposal Methods						5.4
Evaluation of Alternative FGD Waste Disposal Sites	J. W. Jones IERL Research Triangle Park, NC	R. R. Lunt Arthur D. Little, Inc. Cambridge, MA	Jul 1975	54	Technical analysis, laboratory and field tests[c]	5.4.1

(Continued)

TABLE 2. PROJECT STATUS (Continued)

Project Title	EPA Project Officer	Contractor Project Director	Start Date	Estimated Duration, months	Type of Study	Section
New FGC Waste Utilization Methods						5.5
Lime and Limestone Scrubbing Waste Conversion Pilot Studies	J. W. Jones IERL Research Triangle Park, NC	A. G. Sliger Pullman Kellogg Company Houston, TX	1977	11	Bench, pilot plant	5.5.1
Fertilizer Production Using Lime and Limestone Scrubbing Wastes	M. C. Osborne IERL Research Triangle Park, NC	J. L. Crowe TVA, Energy Research Chattanooga, TN	May 1975	41 (plus 18 for field tests)	Pilot plant, field tests	5.5.2
FGD Waste and Fly Ash Beneficiation Studies	J. W. Jones IERL Research Triangle Park, NC	J. Blumenthal TRW Systems Group Redondo Beach, CA	Mar 1976	6 (completed)	Conceptual design, bench, pilot plant	5.5.4
Improving Overall Power Plant Water Use						5.6
Assess and Demonstrate Power Plant Water Reuse and Recycle	J. W. Jones IERL Research Triangle Park, NC	D. M. Ottmers Radian, Inc. Austin, TX	July 1975	13	Analysis of field data, computer simulation	5.6.1
Treatment of Flue Gas Scrubber Waste Streams by Vapor Compression Cycle Evaporation	M. C. Osborne IERL Research Triangle Park, NC	L. D. Weimer Resources Conservation Company Renton, WA	Jul 1976	11	Conceptual design, economics, bench and pilot plant tests	5.6.2
Power Plant Cooling Tower Blowdown Recycle by Vertical Tube Evaporator with Interface Enhancement	M. C. Osborne IERL Research Triangle Park, NC	H. H. Sephton U of California Berkeley, CA	Aug 1974	23	Pilot plant tests	5.6.3

[a] Updated to reflect current EPA project officers

[b] Change since last report

[c] Phase II initiated July 1976

SECTION II

CONCLUSIONS

2.1 BACKGROUND

This report summarizes and assesses the state of research and development (R&D) in the fields of flue gas cleaning (FGC) waste treatment, disposal, and utilization, as well as water recycle and reuse for coal-fired utility power plants, with the ultimate objective being directed toward definition of cost-effective, environmentally acceptable methods. A survey of the work being conducted indicates that a significant portion of effort is currently being conducted under the direction of the U.S. Environmental Protection Agency (EPA). Considerable efforts are also being conducted by others, including utilities and industrial organizations. Although most of these efforts are concerned with problems of a site-specific nature, they contribute to the overall understanding of the technical field under study.

Several EPA studies have been completed, while others have been expanded in scope. In addition, many of the EPA studies are in early stages relative to the availability of quantitive data and will require approximately one to two years to complete. Therefore, firm conclusions regarding a major portion of the laboratory results to date are not warranted at this time. However, some conclusions can be drawn relative to the EPA program scope and its potential to meet program objectives, and observations can be made on the basis of information currently available. These augment and expand those provided in the first annual report; the composite is provided in Section 2.2.

2.2 CONCLUSIONS AND OBSERVATIONS

Federal regulatory guidelines have not been promulgated which could be used to gauge the effects of flue gas desulfurization (FGD) waste disposal on the quality of groundwater and on land reclamation. The results from this program are providing a data base for defining waste disposal standards, predicting effects on groundwater and surface water quality, and determining the structural quality of disposal sites.

Specific observations are as follows:

a. Chemical characteristics of FGC wastes have been found to be a function not only of the properties of coal and scrubber absorbent but also of the manner in which the scrubber is operated, primarily, the pH of liquor in the scrubber. The influence of operating variables on waste characteristics is being systematically studied as part of the program.

b. Removal of fly ash upstream of the scrubber does not completely eliminate the presence of trace elements in leachates of untreated wastes.

c. Physical and chemical properties of untreated and treated FGD wastes and liquors for lime, limestone, and double alkali scrubber systems, using Eastern and Western coals are reported. The resultant properties are process- and fuel-dependent.

d. Results of tests of FGC wastes have shown that chemical treatment significantly improves the structural characteristics of the FGD waste, reduces the solubility of major chemical species by a factor of two to four, and reduces permeability by an order of magnitude or more. No appreciable reduction of the concentration of trace elements in the leachate has been noted when compared to untreated wastes. These observations are being borne out by analysis of results from a field disposal evaluation. Management of disposal sites to prevent collection of surface water would be a significant factor in minimizing or eliminating seepage through the waste. Analysis of groundwater from a field evaluation site with a low permeability clay soil has shown that the presence of the disposal ponds has not yet affected the quality of the groundwater near that site after two years of observation.

e. Load-bearing strengths acceptable for land reclamation purposes have been achieved with untreated lime scrubber sulfite-rich waste placed in an underdrained test disposal site. Monitoring of physical and leaching characteristics will continue. Disposal of limestone, sulfite waste, and gypsum will also be evaluated.

f. With the increased acquisition of quantitative information anticipated during the program, a data base will be formed with which to determine the migration of major species and trace elements from FGD waste disposal sites and to assess the feasibility and environmental impact of alternative disposal sites such as landfills, ponds, mines, and oceans. A compilation categorizing the power-generating industry, location of FGD sources, state of the art of FGD system control technology, current waste treatment and disposal has been prepared. Consideration of environmental impacts of waste disposal is also included. This data base is to be expanded so that it can be used by the EPA to define waste disposal guidelines.

g. The economics of FGD waste disposal and utilization are being defined in detail and will be available for assessment of the various disposal and utilization options. Engineering estimates of 30-year average total fixation and disposal costs (capital and operating) for a typical 1000-megawatt (MW) plant were identified as $7.30 to $11.40 per ton of sludge (1976 dollars and dry weight basis). These estimates represent the range of costs for three different chemical treatment processes. The costs equate to $2.07 to $3.24 per ton of coal and 0.9 to 1.4 mills per kilowatt hour (kWh). Costs of disposing of untreated FGD wastes in lined ponds have been reported as approximately 75 percent of the fixation-disposal costs.*

h. Chemical and physical characteristics of pilot plant produced gypsum by forced oxidation have been determined. Engineering estimates have indicated that the cost of saleable gypsum produced by this process can be competitive with domestically mined crude gypsum if appropriate cost avoidance credits are taken for chemical treatment and disposal. The suitability of the material in actually producing wallboard has not been determined. The desirability of producing gypsum for disposal can be competitive with chemical treatment disposal processes under certain conditions. Factors such as improved scrubber operation may improve the attractiveness of the approach.

i. Technically promising candidates that minimize environmental impacts in the disposal of FGD waste in mines and in the ocean have been identified. Mine disposal, particularly coal-mine disposal, appears attractive and is being considered by industry. Ocean disposal is still under study to better understand the potential effects of certain chemical and physical characteristics of FGC waste on the environment. Further study in quantifying these properties and assessing their impact is currently under way.

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*For sites with bases of natural clay, the cost is approximately 40 percent of fixation-disposal.

j. Results, to date, of studies of recycle and reuse of water from major streams from utility power plants have shown that much more efficient water use can be obtained, in many cases without significant expense, and that evaporation systems are more generally applicable to treating major streams.

k. An economic study of an alumina extraction process utilizing FGC waste as a source of calcium has been completed, and the limitations under which this method of utilization may be competitive with bauxite have been defined. Several key processing steps have also been identified that require experimental verification.

l. Work performed by utilities and chemical processors has ranged from laboratory research on processes and characteristics of wastes to field evaluation of pilot plants and prototype treatment processes. The work has focused on site-specific problems of waste treatment and disposal faced by the utilities involved. The Electric Power Research Institute (EPRI) has initiated a project on the disposal of wastes from FGC processes. The published results and planned effort, in general, complement and augment the EPA program.

m. As of December 1976, 9 stations have 15 units (7484 MWe) committed to full-scale chemical treatment and disposal of FGD wastes through 1979. Of these, five units (2100 MWe) are now in operation, and startup by seven others (3959 MWe) is planned by the end of 1976. Also, 16 plants representing 3646 MWe are identified as scrubbing and disposing untreated lime-limestone scrubbed FGC wastes in lined or in natural clay unlined ponds in 1976 (Ref. 2).

SECTION III

RECOMMENDATIONS

3.1 BACKGROUND

In the first research and development (R&D) report (Ref. 1), review and assessment was conducted of all known R&D activities for flue gas cleaning (FGC) waste treatment, disposal, and water reuse to determine the completeness of the coverage regarding a total understanding of the problems and potential solutions. This report updates and augments the information previously reported. Generally, the current work, funded primarily by the U.S. Environmental Protection Agency (EPA), addresses a broad range of questions that must be answered prior to defining environmentally and economically sound flue gas desulfurization (FGD) waste disposal methods. A project sponsored by the Electric Power Research Institute (EPRI) is expected to expand the data base and provide an independent evaluation of waste treatment and disposal processes, as well as defining disposal guidelines. The results from the EPA program, together with work being done by utilities and other organizations, are forming a significant data base to assist in achieving the stated objectives.

3.2 RECOMMENDATIONS

At present, no specific change in the direction of the EPA-sponsored program objectives is recommended. The various projects are complementary, and negligible duplication of effort has been noted within the EPA program and between the EPA projects and work being conducted by others. For complete coverage of the problem, further consideration of the following recommendations should be given. The first two recommendations were identified in the first annual R&D report; projects concerning these recommendations are not yet under way.

a. In laboratory testing conducted as part of the EPA program, it has been determined that weathering may deteriorate the physical properties of treated wastes. However, the data are limited, and followup work is recommended to define realistic test conditions and quantify the freeze-thaw wet-dry effects on the strength, permeability, and leaching characteristics of treated wastes.

b. Although the EPA program will result in the compilation of a data base encompassing the technology and properties of FGD wastes whereby disposal criteria can be defined and environmental impacts assessed, a series of detailed case studies are recommended where conditions at typical disposal sites in various regions of the United States may be evaluated. Based on the type of waste produced at each site, together with geological, climatalogical, and hydrological factors and site management techniques, an assessment of pollutant transport phenomena, environmental acceptability, and impact of various disposal methods can be made.

c. In the course of evaluating the results of leaching tests, it has become apparent that a need exists to develop and standardize appropriate laboratory test methods to assess and ultimately predict disposal site pollution potentials of FGC wastes. Individual laboratories have tended to devise procedures based on their best appraisal of the problem. While in most cases the data are useful, results between laboratories, in most cases, do not correlate. Therefore, efforts to standardize leaching methods are needed.*

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*It should be noted that the EPA Office of Solid Waste has proposed a toxicant extraction procedure (which involves a shake test with a small sample of the waste under study) to be used in hazardous waste testing under the Resource Conservation Recovery Act (RCRA). Efforts are also under way at the American Society for Testing and Materials (ASTM) to devise a standard leach test.

SECTION IV

SUMMARY

This second report summarizes and evaluates the research and development (R&D) work conducted during calendar year 1976 in the field of coal-fired utility power plant flue gas cleaning (FGC) waste treatment, disposal, and utilization and overall power plant water recycle and reuse. It supplements the information provided in the first annual R&D report (Ref. 1). The results of the various projects being funded by the U.S. Environmental Protection Agency (EPA) and private industry are viewed with the ultimate objective of recommending environmentally acceptable, cost-effective waste disposal and utilization methods.

4.1 APPROACH

Twenty-one EPA projects encompass the areas of (1) technology and economic assessment of existing FGC waste treatment, disposal, and utilization processes; (2) development of new or evolving technology of treatment, utilization, and disposal; and (3) development of methods to improve overall power plant water use.

Some of the EPA projects have recently been initiated, while others have been under way for several years. The projects that address the physical and chemical characterization of the FGC wastes have been funded for the longest periods. Therefore, considerable information required in the evaluation process in these areas is available and is summarized (Figure 2). This report includes data available through November 1976; other significant information published during preparation of this report is also included.

4.2 EFFECT OF PROCESS VARIABLES

A number of variables affect the chemistry of the various process streams and result in different chemical characteristics and properties of the materials to be disposed.

The results were based on chemical analyses of samples from seven different scrubbers having capacities ranging from 1 to 125 MWe and were reported as a function of location within a scrubber circuit as well

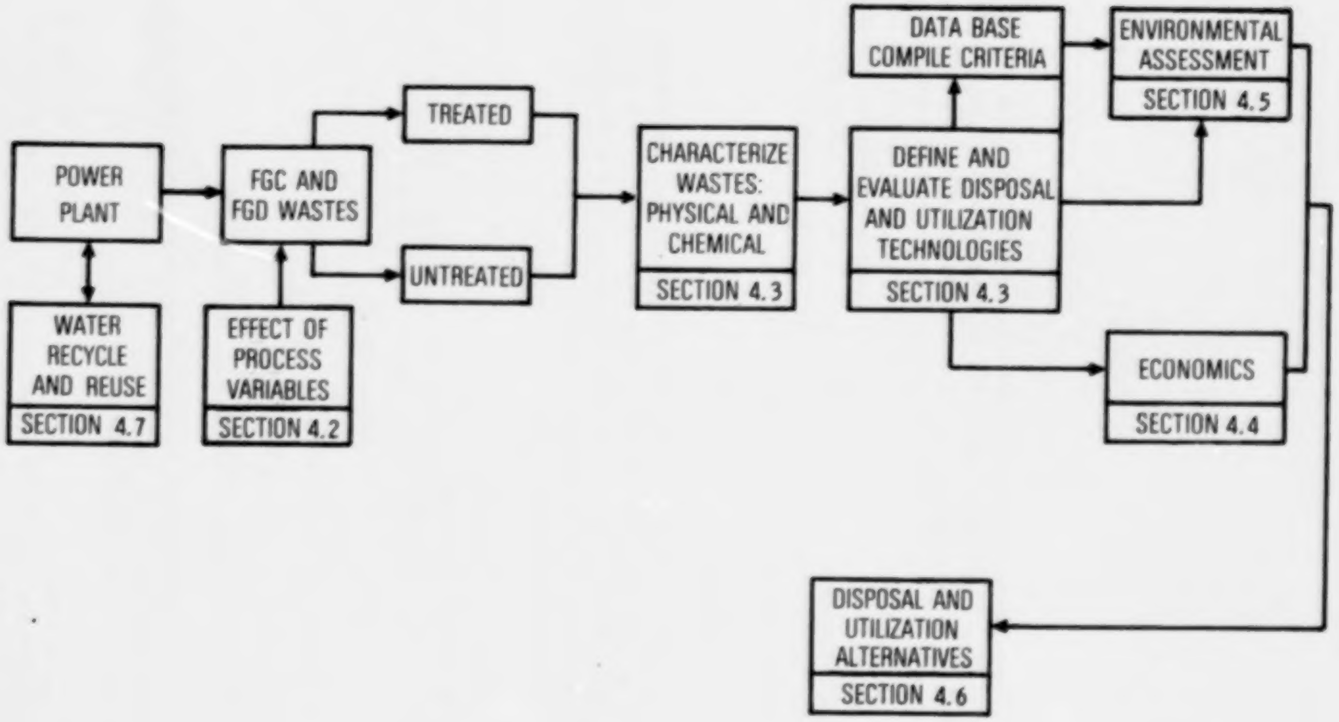

POWER PLANT
WATER RECYCLE AND REUSE
SECTION 4.7
FGC AND FGD WASTES
EFFECT OF PROCESS VARIABLES
SECTION 4.2
TREATED
UNTREATED
CHARACTERIZE WASTES: PHYSICAL AND CHEMICAL
SECTION 4.3
DATA BASE COMPILE CRITERIA
DEFINE AND EVALUATE DISPOSAL AND UTILIZATION TECHNOLOGIES
SECTION 4.3
ENVIRONMENTAL ASSESSMENT
SECTION 4.5
ECONOMICS
SECTION 4.4
DISPOSAL AND UTILIZATION ALTERNATIVES
SECTION 4.6

Figure 2. EPA program evaluation approach.

as a function of time, pH, absorbent, and coal composition (Ref. 1). These included the effects of time, pH, and absorbent in scrubber liquor trace element concentration, as well as the effects of coal composition and solid and liquid waste trace element concentration.

A systematic evaluation of a number of operating variables on solid waste properties is being conducted by TVA at their Shawnee 10-MWe scrubber test facility. The specific form in which the sulfite species appears has been found to be directly related to the type of absorbent used (lime or limestone) and independent of the scrubber configuration [turbulent contact absorber (TCA) or venturi spray tower]. The average size of the sulfite platelets (crystals) formed from the limestone system appears to be inversely related to the system stoichiometry; i.e., the better the limestone utilization, the larger the crystals that are formed. No specific relationship has been seen in the lime system.

4.3 PHYSICAL AND CHEMICAL CHARACTERISTICS OF WASTES

4.3.1 Physical Properties

Properties that define handling and engineering characteristics of untreated and treated sludges have been presented in the first annual R&D report (Ref. 1). These included viscosity, bulk density, and dewatering characteristics; porosity; permeability; and unconfined compressive strength.

Viscosity is a major factor in determining pumping power requirements. Bulk density data are needed in defining the volume of waste and disposal site acreage, and dewatering characteristics are important in defining treatment or conditioning requirements as well as achieving the potential of reducing bulk densities. Compressive strength provides a measure of structural quality. Porosity and permeability determine rate of leachate penetration through the solid waste mass. Therefore, the rate and quantity of leachate constituents entering the ground, i.e., mass loading, can be defined.

4.3.1.1 Viscosity

The viscosity of FGD wastes from seven power plants was presented as a function of solids content in Ref. 3. Properties of six more wastes were determined and are included in Figure 3. The measured viscosity curves generally exhibited the same shape. The results show that, of the wastes tested, the maximum solids content of pumpable mixtures (< 20 poise) range from a high of 70 percent for the Arizona Public Service (APS) Cholla limestone sample to a low of 32 percent for both the Utah Power and Light (UPL) Gadsby and General Motors Parma (GM) double alkali samples. Considering this wide range of maximum solids content, the importance of experimentally determining the viscosity becomes evident. Considering the similarity of the curve shapes, it is also apparent that the dewatering properties are significant in defining the range of solids content over which the fluidity of the mixtures is such that pumping can be considered.

CURVE	SLUDGE	FLY ASH, %	DATE
1	GM PARMA DOUBLE ALKALI	7.4	7/18/74
2	UPL GADSBY DOUBLE ALKALI	8.6	8/9/74
3	TVA SHAWNEE LIME	40.5	3/19/74
4	DLC PHILLIPS LIME	59.7	6/17/74
5	TVA SHAWNEE LIMESTONE	20.1	2/1/73
6	TVA SHAWNEE LIMESTONE	40.1	6/15/74
7	TVA SHAWNEE LIMESTONE	40.9	7/11/73
8	SCE MOHAVE LIMESTONE	3.0	3/30/73
9	APS CHOLLA LIMESTONE	58.7	4/1/74
10	LG&E PADDY'S RUN CARBIDE LIME	12.4	7/76
11	TVA SHAWNEE LIME	<1.0	9/8/76
12	TVA SHAWNEE LIMESTONE	<1.0	9/28/76
13	GPC SCHOLZ SODA ASH DOUBLE ALKALI	<1.0	6/20/76
14	GPS SCHOLZ SODA ASH DOUBLE ALKALI	30.0	6/27/76
15	TVA SHAWNEE LIME	40.0	9/8/76

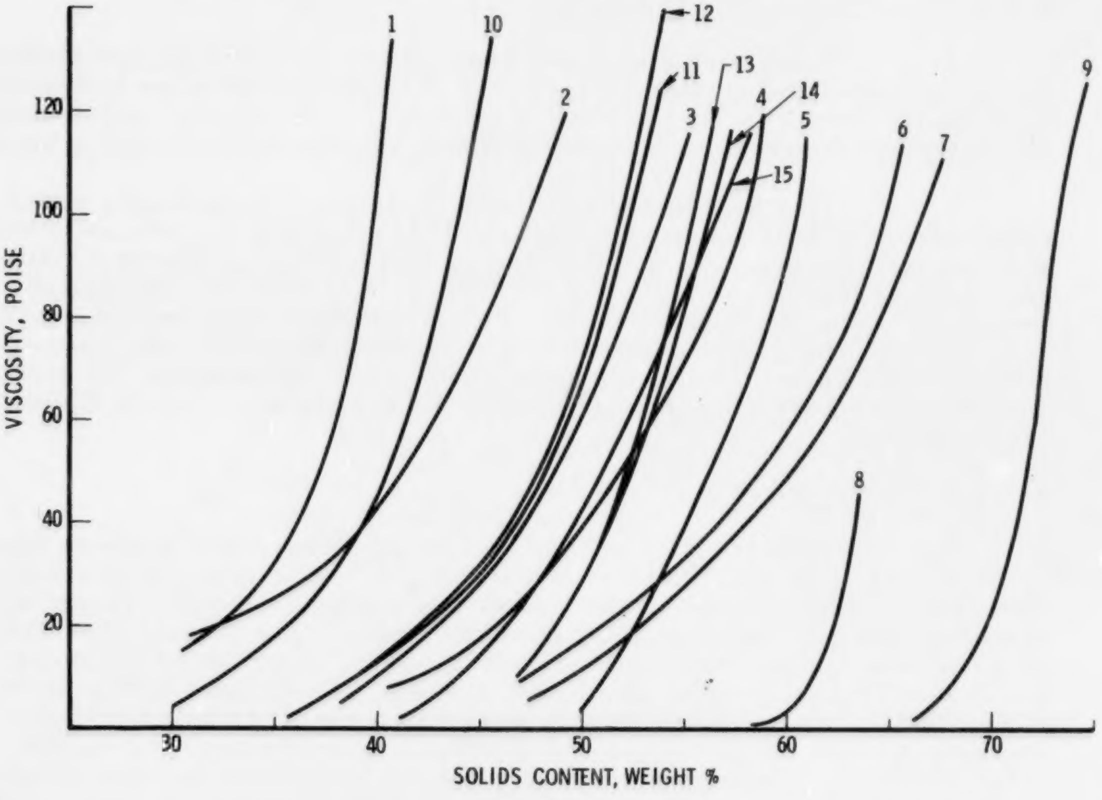


Figure 3. Viscosity of desulfurization sludges.

Test results suggest that the presence of fly ash in FGD wastes decreases the viscosity of FGD slurries, but the magnitude of change is sludge-dependent (Figure 3).

4.3.1.2 Bulk Density and Dewatering Characteristics

The dry bulk density of untreated FGC wastes was reported (Ref. 3) to be in the range of 0.75 to 1.01 g/cm^3 (47 to 63 pcf), the actual value being scrubbing-process and coal-source dependent.

For the wastes examined, chemical treatment increases the dry bulk density to approximately 0.80 to 1.12 g/m^3 (50 to 70 pcf) for wastes with 0.75 g/cm^3 untreated density and 1.28 to 1.76 g/cm^3 (80 to 110 pcf) for those characterized by the higher 1.01 g/cm^3 untreated densities. Again, the coal source and the scrubbing process appear to affect the values.

Dewatering techniques such as settling, draining, centrifuging, and filtration have a marked effect on the resultant bulk density (Ref. 1). Generally, the wet bulk density varied from a low of approximately 1.48 g/cm^3 (92 pcf), settled, to a high of 1.76 g/cm^3 (110 pcf), filtered. Drained and centrifuged values were intermediate to these extremes. These values were determined under laboratory conditions and may not necessarily be representative of results using commercial equipment. However, it is expected that the trends defined will apply. Results of tests with five additional sludges have maintained the same trends and values fall within the ranges previously reported.

Some settling characteristics of wastes from lime and limestone scrubbing processes have been reported by TVA (Section 5.2.33). For the wastes examined, no general relationship has yet been determined between slurry solids content and settling rates because of the strong influence of solids morphology on this property. However, settling rates and behavior for materials of similar particulate composition are generally a function of the slurry solids content, the thicker slurries settling more slowly.

4.3.1.3 Permeability

The permeability coefficients of untreated wastes were reported to be in the range of 10^{-4} to 10^{-5} cm/sec (Figure 4) (Ref. 3). These values are intermediate to typical values for silty sand and sandy clay, which are 10^{-4} cm/sec and 5×10^{-6} cm/sec, respectively. Values as low as 6×10^{-7} cm/sec have been reported for Louisiana Gas and Electric (LG&E) Paddy's Run carbide lime untreated wastes (Section 5.2.1). Consolidation of wastes under pressures of 30 to 100 psi tends to reduce permeability coefficients by factors of from 2 to 5. Chemical treatment tended to reduce permeability by less than a factor of two in some cases and several orders of magnitude in others. The chemical treatment process used, including the solids content of the treated waste, appears to be the major factor in the benefit derived.

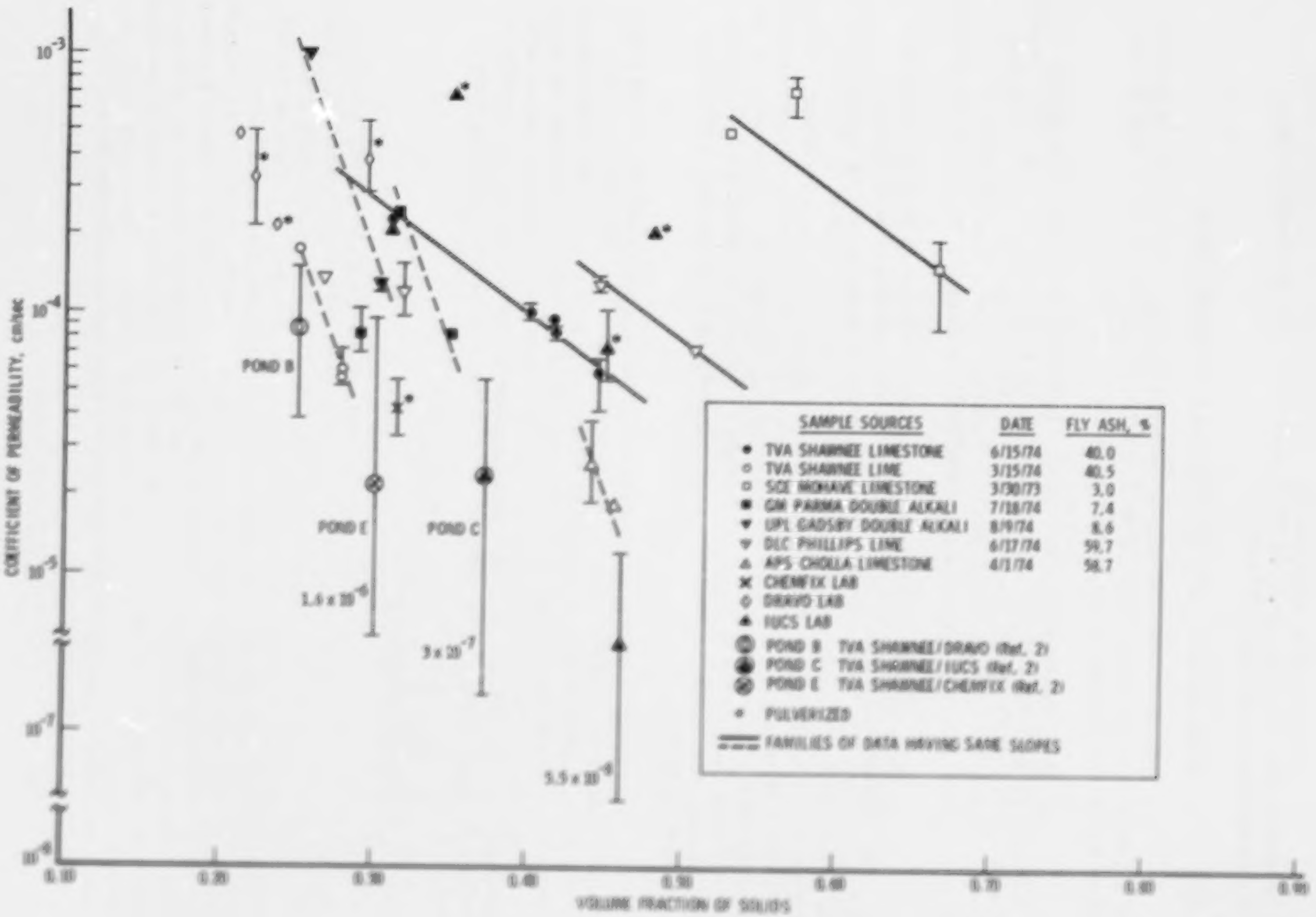


Figure 4. Permeabilities of chemically treated and untreated sludges.

Weathering such as freezing and thawing has been reported to break up the monolithic structure of certain treated wastes (Ref. 4). The permeability of several treated wastes that were mechanically fractured and powered to simulate extensive weathering exhibited permeability values approximately the same as for untreated wastes. Fracturing (but not powdering) and compacting resulted in about one order of magnitude reduction of permeability relative to the powdered condition (Ref. 1).

4.3.1.4 Compressive Strength

Unconfined compressive strength of untreated wastes are low, and no specific values are generally reported because the material is usually too soft to measure. Chemically treated sludges exhibited unconfined compressive strengths ranging from as low as 25 psi to as high as 4500 psi in laboratory studies (Ref. 3). However, commercial processes being used at power stations today produce values in the range of 25 to 400 psi. A systematic evaluation using LG&E Paddy's Run carbide lime sludge at various solids content with carbide lime, lime, and portland cement additives has resulted in unconfined compressive strengths up to 400 psi. Load-bearing strength based on modified soil testing techniques was reported for ten untreated wastes (Ref. 3) (Section 5.1.1.4.6). The influence of settling properties and the criticality of the strength over a narrow range of solids content are illustrated in Figure 5.

4.3.2 Chemical Properties

Chemical properties of scrubber waste liquors and solids and FGC waste leachates have been reported (Ref. 1). More data are becoming available on FGC waste leaching characteristics as the program progresses and are being used to define long-term trends.

Chemical, x-ray, and scanning electron microscope analyses of the solid fractions of the wastes have continued to show the uniqueness of the characteristics, with properties affected by coal composition and scrubber operating variables (Ref. 3).

4.3.2.1 Quality of Scrubber Liquors

The range of concentrations of scrubber liquor constituents were reported (Ref. 3). The soluble chemical content of FGD sludge liquors typically have approximately 10,000-mg/ℓ total dissolved solids (TDS) (steady state), except for double alkali scrubbers, whose liquors have a much higher TDS (Section V, Table 5). The distribution of trace elements in systems liquors tends to lie between 0.01 and 1 ppm for all elements except mercury, which has a concentration distribution of about one-tenth [illegible] of other trace elements.

Some limited data representing the effect of fly ash collection ahead of the scrubber on trace element concentrations in the sludge liquors are reported (Ref. 3). From an assessment of the data, fly ash appears to represent the major source of trace elements in the sludge. The most volatile elemental species (e.g., mercury and selenium) that are scrubbed from flue gases are present in comparable concentrations regardless of whether fly ash is collected upstream of the scrubber.

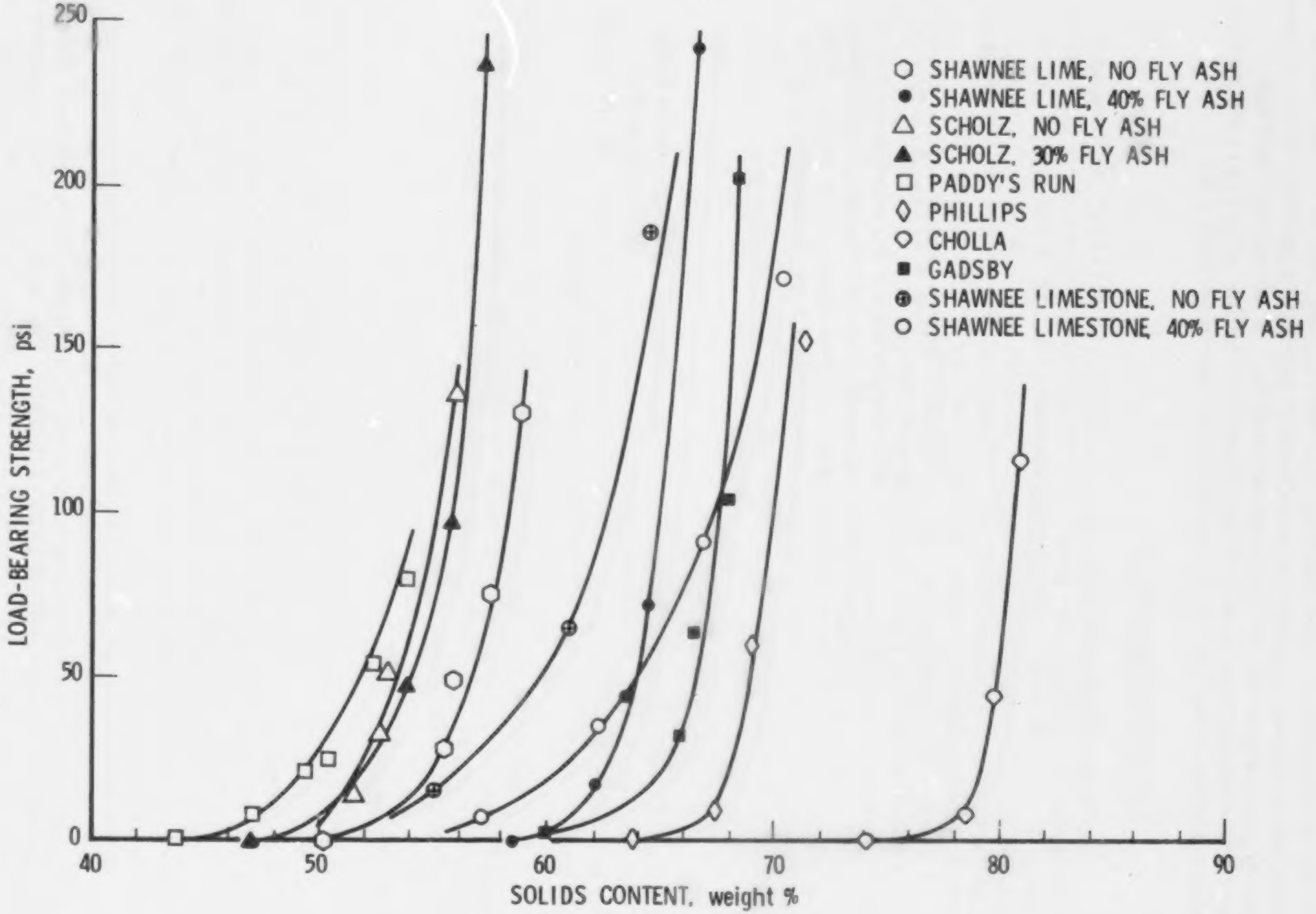


Figure 5. Compression strength of sludges and sludge and fly ash mixtures as a function of solids content.

4.3.2.2 Leaching Characteristics

4.3.2.2.1 Untreated Wastes

From an overall assessment of leaching data, it was concluded that for the major species, i.e., sulfate and chloride ions and TDS, concentration in the leachate decreases rapidly during the first three pore volume displacements (PVD), where about 90 percent of the decrease takes place relative to the fifth pore volume (Ref. 3). The concentrations at the 50th pore volume are approximately the same as at the 5th.

For untreated wastes, the pH of the leaching solution showed no discernible effect on the leachate except for the trace elements lead and zinc, which were leached more readily by acidic conditions. Solubility testing of fly ash showed only Cd, Cu, and Pb concentrations higher at an acidic pH of 4.0 than at 7.0.

4.3.2.2.2 Treated Wastes

No data in addition to that reported in Ref. 3 was available, and the following discussion generally repeats the information presented in the first R&D report (Ref. 1). As with untreated wastes, the reduction of major species concentrations generally takes place within the first three pore volumes.

On the basis of laboratory and field test results, it was reported that the concentration of the TDS in the first pore volume of the treated leachate is approximately 50 percent of the untreated sludge leachate (Ref. 3). After the initial flushing period of three to five pore volumes, the concentrations generally remained constant thereafter, with values from the treated wastes being approximately 25 to 50 percent of those from the untreated wastes.

On the basis of somewhat limited leaching tests evaluating five chemical treatment processes, another laboratory has reported mixed results relative to improvement in the leachate quality from treated wastes (Ref. 4). However, further testing is being conducted, as planned, to verify initial trends and to permit an assessment of the performance of each of the five individual chemical processes.

The effect of chemical treatment on immobilizing trace elements was reported previously (Ref. 3); i.e., no discernible difference was observed when compared to untreated materials because of low concentrations and significant scatter in much of the data. With additional leaching data expected (Ref. 4) and utilization of statistical techniques, it may be possible to determine the effect of chemical treatment. Also, some evidence suggests that in certain instances the additives used in the chemical treatment of FGD wastes may be contributing trace metals to the leachate.

4.4 DISPOSAL ECONOMICS

4.4.1 Chemical Treatment and Disposal

Engineering estimate costs for disposal of chemically treated FGC wastes from a 1000-MWe plant burning Eastern coal were reported previously (Ref. 5) and are repeated here for the convenience of the reader. The total disposal costs, in 1975 dollars, on a 30-year average are as follows:

a. Sludge, including fly ash, per ton (dry basis): $7.30 to $11.40

b. Coal per ton (Eastern): $2.07 to $3.24

c. Mills per kilowatt-hour: 0.9 to 1.4

These costs represent the range of estimates for three fixation-disposal processes. The average annual operating load factor was assumed to be 50 percent over a 30-year lifetime, with the disposal site 5 miles away from the power plant. Locating the disposal site 0.5 miles from the power plant rather than 5 miles and increasing the annual average operating load factor from 50 to 65 percent reduces the disposal costs by approximately 9 and 7 percent, respectively. More detailed cost analyses of several disposal processes will be conducted by the Tennessee Valley Authority (TVA), and results from this study will be reported as they become available.

4.4.2 Ponding

Ponding costs available from Reference 1 are reported herein. Disposal pond costs are dependent on construction and material factors as well as land costs. For materials costing $2.20 to $3.80 per square yard, which represent a reasonable range of liner material costs, the disposal costs on a dry weight basis for a 1000-MW plant are $5.70 to $7.80 per ton of dry sludge, or approximately 75 percent of those for chemical treatment and disposal.

The cost of underdraining systems is in preparation and is expected to be available in the next report.

4.4.3 Forced Oxidation to Gypsum

Engineering cost estimates were reported (Ref. 6) for a tail-end oxidation process approximating the Japanese processes producing saleable gypsum and an integrated system similar to that being tested at the EPA Research Triangle Park (RTP) facility by R. Borgwardt. These are presented in the following table, for a 500 MWe plant, on a 30-year average, at a load factor of 50 percent, and in 1977 dollars. If a cost-avoidance credit is taken for not treating and disposing the FGD waste, gypsum produced by forced oxidation becomes competitive with domestically mined gypsum.

Process	Cost, $/ton dry gypsum	Net cost, $/ton dry gypsum[a]	Domestic gypsum fob at mine, 1975 $
Tail-End	15.62	4.84	4.80
Integrated	11.09	0.31	4.80

[a] Assuming a disposal cost of $9/ton dry sludge

The above estimates are for 100 percent limestone utilization. For a calculated 65 percent utilization, the net costs are $6.73 and $2.22 per ton dry gypsum, respectively, for the tail-end and integrated processes. Conditions under which it may be economically feasible to oxidize and dispose the gypsum are also presented. Since the conditions are somewhat restrictive, the reader is referred to Section 5.1.1.5.3 for a more definitive discussion.

4.4.4 Mine and Ocean Disposal

In conjunction with the work described in Section 5.4.1 to assess the potential and the environmental impacts associated with disposal of FGC wastes in mines and in shallow and deep ocean sites, estimates of capital and operating costs were made for five ocean disposal and six mine disposal options. As a basis, a 500-MW power plant, burning typical Eastern coal (3.0% S, 10.0% ash, and 0.85 lb of coal/kWh) was assumed producing 365,000 tons per year of dry sludge (including ash). The sludge (with ash) was considered to be available either as a dry filter cake (50 percent solids), a 35 percent solids slurry (thickener underflow), or treated sludge. No estimates were included for sludge processing such as filtration, drying, fly ash addition, or treatment. However, in cases where treated sludge required handling, estimates for excavation of treated sludge from stabilization ponds were included. Capital costs were based on 1978 completion of construction and included installed equipment cost for the battery limits disposal system (transfer, handling, and placement), engineering and contractors' fees, working capital, owners' expense, startup, and interest and escalation during construction. Capital investment and operating costs did not include sludge processing equipment, site preparation, land cost, auxiliary utilities, or fees for permits.

For untreated sludge, costs including transfer and intermediate storage ranged from $3.00 to $3.50 per dry ton for onsite disposal to $6.50 to $8.00 per ton for offsite disposal. Disposal of treated sludge in surface area mines increased costs approximately $2.00 to $2.50 per ton to account for excavation of stabilization ponds. The estimates did not include site monitoring costs, which are a strong function of the hydrology, sludge characteristics, and parameters (species) to be measured. To determine overall disposal system costs, sludge treatment costs, as appropriate must also be added to these transfer and placement costs.

In preparing the ocean disposal cost estimates, it was assumed that the sludge was produced in an Eastern power plant with ready access to the ocean and test facilities for berthing disposal craft were available with sufficient area for installation of a sludge transfer and storage system. In all cases studied, the system costs utilizing self-propelled ships were found to be less than for tug-barge combinations because of the lower capital investment for fewer ships, resulting from their shorter cycle times.

Disposal of untreated filter cake (with ash) on the Continental Shelf was estimated as $4.00 to $5.00 per dry ton of sludge, with additional costs of about $2.00 to $2.50 per dry ton resulting from excavation of stabilization ponds for treated sludges. Deep ocean (off-shelf) disposal of filter cake or treated sludge increased costs by $3.00 to $4.00 per dry ton more than shallow (on-shelf) ocean disposal. Disposal of thickener underflow in the deep ocean was estimated to cost approximately $1.00 more per ton than filter cake disposal. As with mine disposal costs, these estimates did not include monitoring costs or sludge treatment costs.

4.4.5 Alumina Extraction

A preliminary process design and economic evaluation of a method for the utilization of lime and limestone scrubbing wastes has been completed (Section 5.5.4). The FGC wastes were used as a source of calcium in the extraction of alumina from low grade domestic ores such as clays or coal ash. The other principal feedstocks for the process were soda ash and coal. The products were alumina for use in aluminum production, elemental sulfur, and dicalcium silicate, an alternative material for use in producing portland cement.

The process design was based on co-locating the conceptual processing plant with a 1000-MW coal-burning power plant in order to receive more than 1,000,000 tons per year (TPY) of lime or limestone FGC scrubber wastes. In addition to scrubber wastes, the process will require, on an annual basis, 12,000 tons of soda ash, 300,000 tons of clay, and 273,000 tons of coal to produce 70,000 tons of alumina, 156,000 tons of sulfur, and 625,000 tons of dicalcium silicate. Dicalcium silicate would be used to feed a cement manufacturing facility producing 860,000 tons of portland cement per year.

The results of this study indicate that an alumina extraction process employing calcium sulfate or sulfite sludge, sodium carbonate, and kaolin clay as reactants could be commercially feasible under present economic conditions provided that the alumina extraction plant includes a cement-producing facility which utilizes the dicalcium silicate by-product from the alumina extraction process. Should bauxite prices escalate, the estimated selling price for alumina as output from an alumina plant not possessing a cement facility may become competitive (Section 5.5.4).

4.5 ENVIRONMENTAL ASSESSMENT

4.5.1 FGC Waste Properties

Data from the various projects are not sufficient for a detailed overall environmental assessment of the effects of land disposal on water quality and land reclamation. However, certain trends are emerging and are summarized herein. It is expected that these will be updated and possibly modified as additional data become available.

It has been determined that untreated waste chemical and morphological properties tend to be a function of the coal and more importantly a function of the scrubbing process variables. The morphology tends to establish the settling and dewatering characteristics of a particular slurry. Detailed characterization of scrubber solid as a function of scrubber operating parameters on the properties are being conducted. Furthermore, chemically treated waste characteristics are also dependent on the treatment process itself. Prime factors to be considered in the disposal of FGD wastes are as follows.

4.5.1.1 Structural Strength

Because of their rheological and structural characteristics, untreated wastes cannot typically support personnel and equipment. Treated material, depending on the fixation process and the solids content, can be expected to achieve strengths in excess of those considered minimal for supporting personnel and equipment and, in some cases, building structures. The long-range effect of weathering on strength, i.e., the effect of wet-dry and freeze-thaw cycling, is yet to be defined.

4.5.1.2 Permeability

Permeability coefficients of untreated materials are in the range 10^{-4} to 10^{-5} cm/sec. Chemical treatment tends to reduce these values over a broad range, from negligible to several orders of magnitude, depending on the process, chemical additive, and the solid content of the treated material (Sections 4.3.3 and 5.1.3.1.1). The long-range effect of weathering on permeability is yet to be determined.

4.5.1.3 Leachate Concentration

Laboratory and field leaching data have shown that leachate concentrations of major species, i.e., calcium, sulfate, chloride, and TDS, in the leachate from chemically treated wastes are about 25 to 50 percent of the concentrations of major species in untreated materials (Section 5.1.1.3).

4.5.1.4 Leachate Mass Release

The mass release of major constituents into the soil from chemically fixed materials is reduced as a result of a 10- to 100-fold reduction in the permeability of the treated wastes (Section 4.5.1.2), as well as the reduced solubility of major pollutant constituents (Section 6.1.3). Treatment process and mode of disposal, i.e., pond, landfill, or lake, determine the mass loading of pollutants into the soil, which can amount to a reduction of one to two orders of magnitude when compared to untreated materials.

4.5.2 Waste Disposal and Dewatering Methods

4.5.2.1 Field Disposal Evaluation

A project to evaluate and monitor the field-site disposal of untreated and treated FGC wastes has been under way for approximately two years at the TVA Shawnee power plant site (Ref. 5). Its purpose is to determine the effects of several scrubbing operations, waste treatment methods, disposal techniques, soil interactions, and field operation procedures. Test samples of treated and untreated wastes, groundwater, surface water, leachate, and soil cores are being analyzed in order to evaluate the environmental acceptability of current disposal technology.

The analysis of groundwater shows no indication of increases in concentration levels attributable to the presence of any of the ponds.

The TDS and the concentrations of major constituents in the supernates of the untreated and treated ponds increased during dry weather and decreased again when increased rainfall caused additional dilution (Refs. 5 and 7).

Generally, the TDS, SO_4, Ca, and Cl in the leachate from untreated ponds reached the input liquor concentration for these constituents and decreased steadily thereafter. Minor constituents whose concentrations span a range of six orders of magnitude were relatively constant over the period monitored (Ref. 5). The analyses of leachate from the ponds containing treated sludge show data trends similar to the untreated ponds; however, TDS levels consistently remained at a level approximately one-half that of those found in the input liquor. Six minor constituents remained at relatively constant levels throughout the monitoring period, with the exception of the boron level in one treated pond, which increased steadily to a level approaching that of the input liquor.

Late in 1976, an evaluation was initiated at the TVA Shawnee site concerning the environmental effects, settling, and structural characteristics of disposing untreated lime wastes in underdrained field impoundments. Monitoring of limestone and gypsum evaluation sites was started early in 1977.

Other field evaluations of FGC waste test impoundments and full-scale disposal sites are in early stages of implementation by LG&E and U.S. Army Corps of Engineers, respectively.

4.5.2.2 Liner Evaluation

An experimental program to determine the compatibility and effectiveness of 18 liner materials with FGD wastes, liquors, and leachates has been initiated. Material screening tests have been conducted. Materials have been selected, and testing has begun in test cells. The exposure of materials to various wastes has been limited, and definitive information is not available at present. The economics of FGD disposal by ponding is also being assessed.

4.5.2.3 Soil Attenuation Effects

A study to determine the extent to which heavy metals and other chemical constituents of FGC wastes may be expected to migrate through soil in land disposal sites has been initiated. Soil and waste characterization tests are complete. However, work has not progressed to the point where quantitative information on the migration and attenuation of FGD waste constituents has been determined.

4.5.2.4 Waste Dewatering Methods

Studies were initiated to determine dewatering characteristics of FGC wastes and to define areas where improvements can be made in dewatering equipment or techniques. Since the program is in its early stages, quantitative information is not available. However, results from this work are expected to be used in assessing benefits derived from not only a reduction of dewatering equipment size, but also the waste volume handled, disposal acreage, and chemical additives.

4.5.3 Data Base Development

A study establishing a data base for use in the development of FGD waste standards has been completed. It includes a categorization of the power generating industry and the location of FGD waste sources, the state of the art of FGD system control technology, untreated and treated waste characterization, and the current practices in sludge treatment and disposal technology. In addition, such factors as site characterization, health effects, safety, ecological effects, and land use and aesthetics in environmental considerations of FGD sludge disposal are included. Existing and proposed federal and state regulations that may apply to the disposal of FGD wastes are summarized and discussed. The results of this study suggest chemical and physical regulating parameters, as well as one option for regulating FGD sludge disposal to land.

4.6 DISPOSAL AND UTILIZATION ALTERNATIVES

Disposal alternatives being studied include assessment of the environmental effects of disposal of treated and untreated wastes in mines and oceans, as well as in landfills and ponds. Experimental and economic studies evaluating processes to produce usable materials such as gypsum, elemental sulfur, and alumina are also being pursued.

4.6.1 Disposal Alternatives

The preliminary assessment of the technical, environmental, and economic factors associated with the mine and ocean disposal of FGC wastes has been completed.

An initial review identifies four general categories of mines as the most promising candidates: active surface-area coal mines, active underground coal mines, inactive or mined-out portions of lead or zinc mines, and inactive or mined-out portions of active underground limestone mines. In addition to the environmental impacts, each category was reviewed with regard to the alternatives for placement, the physical properties of FGC wastes that would be suitable, the operational impacts, the capacities, and the availability and accessibility (via transportation systems) for FGC waste disposal. As a result of this review, the following mines were determined to be most promising:

a. Active Interior surface-area coal mines

b. Active Eastern and Interior room-and-pillar underground coal mines.

In general, Interior surface-area coal mines appear to be more promising than Western (Rocky Mountain and Pacific Coast) area surface coal mines. However, area surface mines both in the Interior and the West were considered much more promising than Eastern contour surface mines because of the latter's low capacity for FGC wastes and the difficulty for waste placement because of the steepness of slopes in the contour mines. The problem with the Western surface-area mines is the greater potential for groundwater contamination, relative to Interior mines, because of a lower net annual rainfall resulting in less dilution of leachate. In addition, FGC wastes from Western plants burning low-sulfur coal normally contain a higher concentration of dissolved salts.

Individual Interior surface-area mines have substantial capacity for receiving FGC wastes, and disposal is considered technically feasible within existing mine operations. The wastes must be dewatered to the extent necessary for landfill operations, so that they can be dumped into a mined-out strip (which can be adjacent to one being mined) and covered with overburden. Placing FGC waste in the mine void should assist in returning the terrain to its original elevation.

The principal environmental impact anticipated from this disposal method is an increase in TDS in waters that are recharged by leachate from the disposal site. This impact may be lessened by placing part of the overburden in the mined-out strip prior to placing the FGC waste, thereby elevating the waste above the groundwater table. In addition, dilution to acceptable TDS levels can be encouraged by maintaining a suitable distance between the disposal site and the stream or by assuring that the receiving streams have a sufficiently high flowrate.

In assessing the ocean disposal of FGC wastes, various methods of transportation and disposal were examined, including surface craft (e.g., bottom-dump barge and slurry dispersion) and pipeline (outfall). Various chemical and physical forms of the FGC wastes were also considered, i.e., sulfite-rich wastes, sulfate-rich wastes, and treated wastes in both soil-like and brick-like forms. Both Continental Shelf and deep ocean disposal of the wastes were examined.

Until more definitive data are available, disposal of sulfite-rich FGC wastes on the Continental Shelf or in the deep ocean does not appear to be advisable because of protected problems with oxygen demand and sulfite toxicity (from ingestion by marine life). In addition, it appears that all soil-like FGC wastes--whether sulfite or sulfate, treated or untreated--should not be disposed of via quick-dumping surface craft or pipeline (outfall) on the Continental Shelf. Several options that involve surface craft appear more promising:

a. Dispersed disposal of sulfate-rich FGC wastes on the Continental Shelf

b. Concentrated disposal of treated, brick-like FGC wastes on the Continental Shelf

c. Dispersed disposal of sulfate-rich FGC wastes in the deep ocean

d. Concentrated disposal of both sulfate-rich and treated FGC wastes in the deep ocean

4.6.2 Utilization Alternatives

Utilization of FGC wastes can be considered as an alternative to disposal. In this regard, the use of FGD wastes in the manufacture of fertilizer were reported as being studied by TVA and the Illinois Institute of Technology (IIT) (Ref. 1). Although a number of problems relating to preneutralizer operation have been experienced by TVA, potential solutions are being systematically tested. Experiments on the forced oxidation of sulfite sludges to form gypsum for potential use in wallboard were conducted by EPA at RTP (Ref. 8) and by Southern Services at Gulf Power Company (GPC) Plant Scholz, using the Chiyoda process. Wallboard from Chiyoda gypsum, a 50/50 blend with the natural material, has been fabricated. The chemical and physical properties of the gypsum produced by forced oxidation have been determined. The properties specifically related to manufacturing wallboard have not been determined.

Engineering estimates on the cost of producing saleable gypsum have been made and are summarized in Section 4.4. The detailed economics studies of various gypsum-producing processes and a survey of potential markets are also being conducted.

A project to use FGD gypsum in cement manufacturing is expected to get under way in the near future, as is the pilot plant evaluation of key steps in a process that uses FGD waste reduced to CaS in a kiln as a starting material to produce elemental sulfur or sulfuric acid.

A preliminary process design and economic evaluation of a method for the utilization of lime and limestone scrubbing wastes has been completed (Section 5.5.4). The FGC wastes were considered as a source of calcium in the extraction of alumina from low-grade domestic ores such as clays or coal ash. The other principal feedstocks for the process were soda ash and coal, the products being alumina for use in aluminum production, elemental sulfur, and dicalcium silicate, which is an alternative material for use in producing portland cement. Although the chemistry of the process is similar to the lime-soda-sinter reaction, with the exception that it proceeds in a reducing rather than oxidizing atmosphere, a number of technical assumptions were made regarding the chemical functioning of the process. These conditions were identified, and the recommendation that laboratory testing be conducted to determine the validity of the assumptions was made. The economics are discussed in Section 4.4.5.

4.7 POWER PLANT WATER RECYCLE, TREATMENT, AND REUSE

This portion of the Waste and Water Program is designed to evaluate, develop, and demonstrate cost-effective techniques for minimizing water consumption and discharges through recycle and reuse, as well as techniques for treatment of in-plant streams for reuse or discharge within effluent guidelines.

The major limitation in the recycle and reuse of major plant streams (e.g., cooling tower blowdown and ash sluice water) is the buildup of dissolved salts. Chemical treatment to precipitate compounds (e.g., calcium sulfate) can increase the number of cycles in the major systems, but eventually purging of the more soluble salts is required. Treatment of the purge streams may involve use of expensive techniques such as evaporative or membrane processes. Demonstration of the broad-scale applicability of the technology necessary for minimization or elimination of effluents is expected to be provided by this program.

Five power plants are being studied to examine the alternatives for minimizing water use and discharges in the major plant systems, e.g., cooling towers, ash sluice systems, and wet scrubbers. Several water treatment systems are being examined to address the problem of dissolved salts in recycle streams, including vapor-compression cycle evaporation and vertical tube evaporation with interface enhancement (for better heat transfer).

Chemical characterization of water streams from three plants, and computer-assisted simulation of existing plant water utilization operations were completed. Technical assessments were also completed, formulating water recycle and reuse options to minimize water requirements and discharges in major plant systems, e.g., cooling towers, ash sluice systems, and wet scrubbers. Cost estimates of each viable option were also prepared. The plants were chosen to represent regions in the United States where water recycle or reuse would be advantageous because of high water costs, limited availability, or treatment and disposal problems.

The three sites initially selected for this study were the Four Corners Plant of Arizona Public Service (APS), Comanche of Public Service of Colorado, and Bowen of Georgia Power Company. The study has been completed for these locations during the past year, and subsequently similar studies were initiated for Montana Power Company's Colstrip plant and Pennsylvania Power and Light Company's Monitor plant.

Chemical analyses of water samples were conducted, and these results were used as input data to verify a computer model simulating normal plant operations. Subsequently, evaluation of various water recycle and reuse options and strategies for each of the representative plants on the basis of design or design installation, operability, and treatment effectiveness were made with the aid of the model simulations.

Cooling tower and ash sluicing alternatives included use of cooling system blowdown to sluice ash operating at various cycles of concentration, the effect of CO_2 mass transfer on formation of scale, pH control, and treating of the discharge water by lime-soda or reverse osmosis.

Alternatives for the particulate scrubbing system include the effects of using existing tanks as solid-liquid reaction vessels, increasing tank volumes, recycling ash pond overflow, and reducing the fly ash content entering the scrubbers. The sensitivity to the various parameters was determined and reported; several viable options as defined by the technical assessment were made; and the overall optimum recycle or reuse option based on technical and economic considerations for each of the three plants was defined. The results of the study including several alternatives for each specific site and additional testing to verify that key assumptions have been made. Overall recommendations for further assessments or field evaluations are planned and will be available upon completion of the analyses of the Colstrip and Montour plants.

A series of tests to demonstrate the feasibility of using a vertical tube, falling film, vapor-compression evaporator to concentrate waste water from an FGD process will be conducted in the near future: one with a 25-gallon per day bench unit and the other with a pilot size 600-gallon per day evaporator.

The effectiveness of interface enhancement using a surfactant to reduce heat transfer requirements was demonstrated as a means of reducing energy and cost of treating and recycling boiler plant wastewater streams. Tests with 5, 000 and 10, 000-gallon per day evaporation were conducted.

4.8 FULL-SCALE APPLICATIONS

A total of 15 plants, representing 9 utilities and totaling 7484 MWe, are currently committed to initiate, by 1979, the chemical treatment of lime-limestone scrubber wastes prior to disposal. Five stations (2100 MWe) are now in operation; seven (3959 MWe) will start up by the end of 1977; and three have made definite commitments to begin by 1979. Also, 16 plants representing 3646 MWe are identified as scrubbing and disposing untreated lime-limestone scrubbed FGC wastes in lined or in natural clay unlined ponds in 1976 (Ref. 2).

Experience with a limestone wet scrubber, gypsum-producing system operating on Unit 1 at the Northern States Power Company Sherbourne generating plant was described recently (Ref. 9). Unit (700 MWe) became operational in May 1976. The sulfite slurry from the scrubber is air-oxidized in a reaction tank. The gypsum slurry is thickened and pumped to a disposal site. Unit 2 (700 MWe) is scheduled to begin operation in May 1977.

SECTION V

EPA-SPONSORED RESEARCH AND DEVELOPMENT

The U.S. Environmental Protection Agency (EPA) Program for Control of Waste and Water Pollution from Flue Gas Cleaning (FGC) Systems is designed to evaluate, develop, demonstrate, and recommend environmentally acceptable cost-effective techniques for disposal and utilization of FGC wastes, with emphasis on flue gas desulfurization (FGD) waste, and to evaluate and demonstrate systems for maximizing recycling and reuse of power plant water. The program currently consists of 20 projects, encompassing 6 major areas of interest: (1) environmental assessment of FGC waste disposal and utilization processes including other power plant effluents, (2) process technology assessment and new technology development, (3) process economic studies, (4) alternative FGC waste disposal methods development, (5) new FGC waste utilization methods development, and (6) development of methods for improving overall power plant water utilization.

The scope of the EPA FGC waste and water pollution control program is depicted in Figure 1. Projects concerning coal-pile effluents, fly ash, water, and FGC waste (untreated, treated, and as affected by scrubber operation) span the entire spectrum of the FGC waste characterization and disposal assessment problems.

In this report, the specific projects are discussed separately under their respective primary categories as indicated in Table 1. Additional information such as contractor or agency project director, EPA project director, duration, start date, and type of study are provided in Table 2.

5.1 ENVIRONMENTAL ASSESSMENT OF FGC WASTE DISPOSAL

Eight environmental assessment projects are currently under way. These include FGC waste characterization studies; laboratory and pilot field studies of disposal techniques for chemically treated FGD sludges; characterization studies of coal-pile drainage, coal ash, and other power plant effluents; and studies of attenuation of FGC waste leachate by soils.

5.1.1 FGC Waste Characterization, Disposal Evaluation, and Transfer of Waste Disposal Technology (The Aerospace Corporation

The Aerospace Corporation, El Segundo, California, is completing a broad-based study directed toward the determination of environmentally sound disposal of solid and liquid wastes produced in FGD processes. The desulfurization processes of interest in this program are the lime, limestone, and double alkali wet scrubbing of flue gases produced in the combustion of coal in steam power plants. More specifically, problems associated with FGD waste disposal are being defined, and assessments are being made of the operational feasibility, performance, and costs of current disposal methods. In addition, recommendation regarding alternative disposal methods based on these findings are being formulated (Ref. 1). Annual reports are being issued, of which this is the second, in which FGC waste-related research and development (R&D) activities sponsored or conducted by EPA, Tennessee Valley Authority (TVA), and private industry are summarized and assessed.

During this period, emphasis has been placed on enlarging the data base of the physical and chemical characterization of FGD scrubber wastes. Three additional sources (Table 3) were included. Alternative disposal methods encompassing technical and economic factors in producing gypsum by forced oxidation of FGD wastes were assessed. Physical and chemical properties of gypsum relative to its disposal potential were determined. The technical planning, support, and assessment of an EPA FGD waste disposal field evaluation program was continued. The latter is reported in Section 5.1.2.

TABLE 3. FGD SYSTEMS SAMPLED AS DATA BASE

Power Plant	Scrubber System	Scrubbing Capacity MW (equiv)	Coal Source	Absorbent
Tennessee Valley Authority (TVA), Shawnee Steam Plant	Venturi and spray tower, prototype	10	Eastern	Lime
Louisville Gas and Electric Co., Paddy's Run Station	Marble bed absorber	70	Eastern	Carbide lime (slaked lime waste)
Gulf Power Company Scholz Station	Venturi and spray tower	20	Eastern	Soda ash, lime

Results reported in the first annual R&D report (Ref. 1) are summarized briefly to place the entire technical program in perspective. However, details of only the current year's work are provided.

5.1.1.1 Chemical Characterization of Process Streams

Analyses of process streams from seven utility power plants (Table 4, plants 1 through 7), encompassing a wide range of scrubber system capacity, coal sources, and absorbent were reported (Ref. 3). The effect of process variables on the stream characteristics were included and are summarized as follows:

a. The concentration of major chemical species increases with time from startup until a steady-state condition is reached for all species. Trace element concentrations reach steady-state rapidly and are not affected by the steady-state conditions of the major species.

b. The system pH is effective in controlling trace element species only within a defined system where major process parameters are controlled.

c. Western coals, in general, tend to have lower trace metal contents than Eastern coals and significantly lower concentrations of arsenic, cadmium, mercury, and zinc.

d. The major portion of trace metals found in the sludge liquor originates from leaching of the fly ash during the more acid portion of the scrubbing cycle. The contribution made by the process waters is insignificant relative to the contribution from coal; in most cases, the contribution of the absorbent is slight.

5.1.1.2 Chemical Characteristics of Untreated FGC Wastes

Chemical properties of scrubber waste liquors and solids and FGC waste leachates have been reported (Refs. 1 and 3). Data on wastes from three additional sources (Table 4, plants 8 through 10) were obtained during the year and are reported herein.

A description of the chemical analyses is presented in detail in Reference 3 for both liquids and solids.

Chemical, x-ray, and scanning electron microscope analyses of the solid fractions of the wastes have continued to show the uniqueness of the characteristics, with properties affected by coal composition and scrubber operating variables such as pH, liquid-to-gas ratio, and hold-tank residence times.

The effect of process variables on the concentration of chemical constituents was reported as a function of the location within a scrubber circuit, as well as a function of the scrubber process itself, i.e., lime, limestone, and double alkali.

TABLE 4. FLUE GAS DESULFURIZATION SYSTEMS SAMPLED AS DATA BASE

Power Plant	Scrubber System	Scrubbing Capacity, MW (equiv)	Coal Source	Absorbent
1. TVA Shawnee Steam Plant	Venturi and spray tower, prototype	10	Eastern	Lime
2. TVA Shawnee Steam Plant	Turbulent contact absorber, prototype	10	Eastern	Limestone
3. Arizona Public Service Company, Cholla Power Plant	Flooded-disk scrubber, wetted film absorber	120	Western	Limestone, fly ash
4. Duquesne Light Company, Phillips Power Station	Single- and dual-stage venturi	410	Eastern	Lime
5. General Motors Corporation, Chevrolet-Parma Power Plant	Bubble-cap tower	32	Eastern	Soda ash, lime
6. Southern California Edison, Mohave Generating Station	Turbulent contact absorber, pilot plant	<1	Western	Limestone
7. Utah Power and Light Company, Gadsby Station	Venturi and mobile bed, pilot plant	<1	Western	Soda ash, lime
8. TVA Shawnee	Venturi and spray tower, prototype	10	Eastern	Lime
9. Gulf Power Company, Plant Scholz	Venturi and spray tower	20	Eastern	Soda ash, lime
10. Louisville Gas and Electric Company, Paddy's Run Station	Marble bed absorber	65	Eastern	Carbide lime

Note: Sources 1 through 7 are reported in Reference 3.
Sources 8 through 10 are reported in this report.

The concentrations of major chemical species and trace elements in FGD wastes decrease as the sludge passes from the scrubber to the disposal point. However, the constituents are affected differently as they progress through the scrubbing process. An indication of the end-to-end (scrubber stage to disposal stream) changes for the concentrations of various constituents is shown for the limestone process in Table 5 by the relationship of the constituent concentrations of liquors in the scrubber to those in the disposal material.

The range of concentrations of constituents found in 10 different Eastern and Western scrubber liquors is shown in Table 6. A summary of the net changes in the liquor stream between the initial (scrubber) stage and the final stage (disposal stream) for lime, limestone, and double alkali is shown in Table 7.

TABLE 5. RELATIVE CHANGE IN CONCENTRATION OF CONSTITUENTS IN THE SCRUBBER CIRCUIT LIQUOR: LIMESTONE PROCESS

Constituent	Direction of Change	Change from Scrubber Stage to Disposal Stream
Calcium	Decrease	30 to 40%
Chloride	Decrease	20%
Sulfite	Decrease	< 99%
Sulfate	Decrease	10%
Trace Metals	Decrease	10 to 20%
pH	Increase	2 units

5.1.1.2.1 Solids Composition

Dry wastes from three power plants (Table 3), Gulf Power Company (GPC), Louisville Gas and Electric (LG & E) Paddy's Run No. 6, and the EPA two-stage pilot scrubber, were analyzed for their major components. The results of these analyses are shown in Table 8.

Each of the samples contained gypsum in excess of 15 percent (dry basis). Neither the Scholz or the Shawnee sample contained a significant amount of fly ash, but the Paddy's Run sludge contained about 12 percent ash and about 3.5 percent carbon. The Scholz sludge also contained approximately 4 percent sodium salts from the double alkali process. On a dry basis, precipitated calcium carbonate amounted to about 10 percent for the Shawnee and Scholz sludges and almost 30 percent for the Paddy's Run sludge.

TABLE 6. RANGE OF CONCENTRATIONS OF CHEMICAL CONSTITUENTS IN FGD SLUDGES

Scrubber Constituents	Sludge Concentration Range	
	Liquors; mg/l	Solids; mg/kg
Aluminum	0.03 - 2.0	–[a]
Arsenic	0.004 - 1.8	0.6 - 52
Beryllium	0.001 - 0.18	0.05 - 6
Cadmium	0.004 - 0.11	0.08 - 4
Calcium	10 - 2600	(10.5) - (26.8)[b]
Chromium	0.011 - 0.5	10 - 250
Copper	0.002 - 0.56	8 - 76
Lead	0.005 - 0.52	0.23 - 21
Magnesium	0.1 - 2750	–
Mercury	0.00005 - 0.07	0.001 - 5
Potassium	5.9 - 760	–
Selenium	0.0006 - 2.7	2 - 17
Sodium	10.0 - 29,000	(3.7)
Zinc	0.001 - 0.59	45 - 430
Chloride	420 - 33,000	(0.9)
Fluoride	0.6 - 58	–
Sulfate	600 - 84,000	(3.5) - (47.3)
Sulfite	0.9 - 3500	(0.2) - (69.2)
TDS	2800 - 162,700[c]	
pH	4.3 - 12.7	

[a] Not analyzed.

[b] Parentheses indicate weight percent.

[c] Typical maximum: approximately 10,000 (see Section 5.1.1.2.2).

TABLE 7. NET CHANGE IN SCRUBBER LIQUOR COMPOSITION OF MAJOR, MINOR, AND TRACE CONSTITUENTS BETWEEN INITIAL AND FINAL STAGES IN SCRUBBER SYSTEM

Constituent	Limestone[a]			Lime[a]			Double Alkali[a]		
	Increase	Decrease	No Significant Change (<20%)	Increase	Decrease	No Significant Change (<20%)	Increase	Decrease	No Significant Change (<20%)
Aluminum (Al)		XXX			XX	X			
Antimony (Sb)		X			X	XX			
Arsenic (As)	X	X	XXX		XXX	X			X
Beryllium (Be)		XX	XXX			XXXX			X
Boron (B)					X				
Cadmium (Cd)		X	XXX		XX	XX			X
Calcium (Ca)		XXXX			XX	XX			X
Chromium (Cr)	XX	X	XX	X		XX			X
Cobalt (Co)		X				XX			
Copper (Cu)	XX		XXX	X	XX				X
Iron (Fe)		X			XXX				
Lead (Pb)	XX	XX	X			XXXX			X
Magnesium (Mg)	X	X	XX		X	XX			
Manganese (Mn)				X	X				
Mercury (Hg)		XX				XXX		X	
Nickel (Ni)		X			X	X			
Potassium (K)	XXX			XX			X		
Selenium (Se)	XX		XX		X	XXX		X	
Silicon (Si)					XXX				
Silver (Ag)		X			XX	X			
Sodium (Na)			XXXX			XXX			
Zinc (Zn)	X	XXX	X		XXX	X	X		
Chloride (Cl)		XXXX			XX	XX	X		
Fluoride (F)	XX		X	XX		XX			X
Sulfate (SO_4)			XXXX		XX	XX	X		
Sulfite (SO_3)		XXXX			XXX			X	
TDS		XXXX			XX	X	X		
pH	XXXX			XXXX					X

[a] Each "X" represents a separate sample set.

TABLE 8. COMPOSITION OF DRY SOLID SLUDGE FROM THREE POWER PLANTS (WEIGHT PERCENT)

Component	TVA/Shawnee, Lime (Run F)	LG&E/Paddy's Run, Carbide Lime	Gulf/Scholz, Double Alkali	Gulf/Scholz (analysis by A. D. Little, Inc.)
$CaSO_4$[a]	19.4	15.1	15.3	–
$CaSO_4$[b]	–	–	–	13.9
$CaSO_3$[c]	69.2	37.4	68.1	68.1
$CaCO_3$	10.3	29.5	10.1	8.2[d]
Insolubles[e] in HCl	–	15.9[e]	–	–
Na_2SO_4[f]	–	–	3.7	3.5
Total	98.9	97.9	97.2	93.7

[a] Expressed as $CaSO_4 \cdot 2\ H_2O$.

[b] Expressed as $CaSO_4 \cdot 1/2\ H_2O$.

[c] Expressed as $CaSO_3 \cdot 1/2\ H_2O$.

[d] Calculated from excess Ca.

[e] Contained 3.5 percent carbon (loss on ignition [LOI]).

[f] Calculated from Na.

Scanning electron microscope (SEM) examination of the solid phases of each of the ash-free sludges showed the presence of some fly ash particles. The trace elements found in the liquors of ash-free sludge may be explained by the presence of minor quantities of fly ash not removed by the separator. Also, in addition to condensing the volatile elements such as Pb and Hg in the scrubber it is probable that the extremely fine fly ash particles are carried past the separators by the flue gas and are collected in the scrubber. Since the finest fly ash particles can remain suspended in the liquors and leachates and pass through the pores of the filters used during analyses of the liquor, it is possible that these suspended particles are subsequently analyzed as dissolved species. Therefore, not all the reported concentration levels of trace elements may actually represent dissolved species.

Additionally, other input ingredients such as the lime and limestone absorbents may possibly contribute perceptible levels of trace elements to the liquor.

It is concluded from these data, that removal of fly ash ahead of the scrubber will not eliminate the trace elements from the sludge liquors and leachates, but the concentration levels of some trace elements may be significantly reduced (Section 5.1.1.2.3.2).

5.1.1.2.2 Quality of Scrubber Liquors

The range of concentrations of scrubber liquor constituents from eight scrubber systems from seven utility power plants is shown in Table 6.

From these data, several observations can be made that reveal the chemical constituent concentrations that may be expected of liquors in contact with solids from FGD scrubber systems. Among the trace elements in the sludge liquors, the upper limits of the ranges of concentrations are between 0.1 and 1 mg/ℓ with the exceptions of aluminum, arsenic, and selenium, for which the highest values did not exceed 3 mg/ℓ, and for mercury, for which the highest value was 0.07 mg/ℓ. The range of concentrations of most trace elements in the liquor was two orders of magnitude. The range of concentrations found in the solids is similar. However the absolute level of the concentrations in the solids is greater than the liquor by a factor of 100.

The concentration of Be, Cd, and Hg in the liquids and solids are generally low in both phases. Concentrations of chromium and zinc (possibly also copper are high in the solids), but correspondinly high concentrations are not observed in the liquor. Whereas in the first case (Be, Cd, and Hg), the correlation strongly suggests a concentration limitation based on input quantities, in the second case, the lack of correlation suggests that factors relating to system chemistry may be controlling the liquor concentrations of these elements. An apparent exception is selenium. It has the broadest concentration range in the liquor (nearly four orders of magnitude) but has the narrowest concentration range in the solids (factor of eight). In this case, the sample that contributed the high solids content had the lowest pH of all samples analyzed.

Among the major chemical species, the concentrations and range of concentrations were reported as strong functions of the chemical parameters of the system. Sodium, as an example, ranges from a low value of 10 mg/ℓ to nearly 5 percent by weight. The later quantity being in the liquid phase of the double alkali systems. When high values of sodium and sulfate, or chloride, are present, significant amounts of sodium salts can be expected in the solids. As was expected, the solids sample having the highest sulfite content also had the lowest sulfate content. One of the more important chemical parameters in the sludge liquors is the total dissolved solids (TDS) content. Because of the recycle of scrubber liquor and because water is evaporated in the scrubber, the TDS can be expected to be relatively high. In most cases, it can be typically described at 10,000 mg/ℓ. Higher values of about 150,000 ppm were observed for the double alkali samples wherein the solids had not been washed to remove soluble salts. In another instance where a salt brine was used as makeup water, the TDS was high and consistent with the makeup water concentration. Values lower than 10,000 were observed in two systems during startup and a third system in a partial open-loop operation. From these data, it is reasonable to expect values of TDS in scrubber liquors to be approximately 10,000 mg/ℓ for steady-state systems, except in cases having exceptional circumstances, and these cases can usually be identified from system design parameters, e.g., the percent solids in the water stream (degree of water recycled), chloride content of coal, and addition of soluble salts such as MgO.

5.1.1.2.3 Leachate Characteristics

In previously reported studies (Ref. 1), leaching tests were continued until 50 pore volumes had been displaced. In most cases it was observed that 90 percent of the decrease in concentration of major leachable species had taken place after three pore volumes had been displaced. In the studies currently being reported, leaching was not continued beyond 10 pore volume displacements (PVD). The leaching tests were performed under aerobic conditions; other details of the procedures are given in Ref. 3.

Leaching curves were defined by analyzing for TDS at approximately five different PVD values. Complete analyses for major and minor constituents were made only on the first and last leachate PVD sample. Figure 6 illustrates the concentrations of major ionic species (SO_4, Cl, Ca, and Mg or Na) and TDS for the sludge leachates obtained from a TVA Shawnee lime scrubber operation. It shows the results of leaching ashfree lime sludge and sludge remixed with 40-wt % fly ash. For additional comparison, the concentrations of major species and TDS of the sludge liquor (filtrate taken from vacuum filter) have also been plotted. The TDS in the leachates of both sludge samples decreased from initial values comparable to that of the filtrate and leveled off at 2000 to 2500 mg/ℓ after three pore volumes had been displaced. This is approximately the solubility of the calcium sulfate. Similarly, the sulfate leveled off at about 1000 to 1500 mg/ℓ. The calcium concentrations of both samples remained relatively constant at about the 600 mg/ℓ level. In contrast, the magnesium and chloride concentrations decreased to below the 100 mg/ℓ level. The filtrate and leachate analytical data are also shown in Table 9. Data from the LG&E Paddy's Run and the Gulf Power Plant Scholz from Reference 6 are given in Table 10. Although TDS was high for the Scholz double alkali material, approximately 160,000 ppm, it was due primarily to the presence of sodium sulfates. The sodium sulfate fraction was completely leached by the third PVD, and the TDS exhibited calcium sulfate saturation levels.

The leachate from the LG&E sludge at the 10th pore volume differed from the leachate samples of all the other sludges after extended leaching. In that material, the TDS and SO_4 concentrations did not level off at their characteristic gypsum saturation level of 2200 and 1300 mg/ℓ. Lower values observed for the 10th PVD leachate sample from the LG&E Paddy's Run sludge represents under-saturation of the leaching water and indicates that most of the gypsum may have been already dissolved so that saturation was no longer possible.

5.1.1.2.4 Effect of Fly Ash on Leachate Components

Chemical analyses for major components and for 10 selected trace elements are reported for the sludge liquors and leachates from the three power plants (Tables 9 through 11). Analyses for Shawnee sludge filtrate liquor and for leachate samples from leaching tests of both the ash-free sludge and the sludge and fly ash mixture are given in Table 12. Results for both ash-free sludge from Gulf Scholz and sludge containing 30 percent fly ash are given in Table 10.

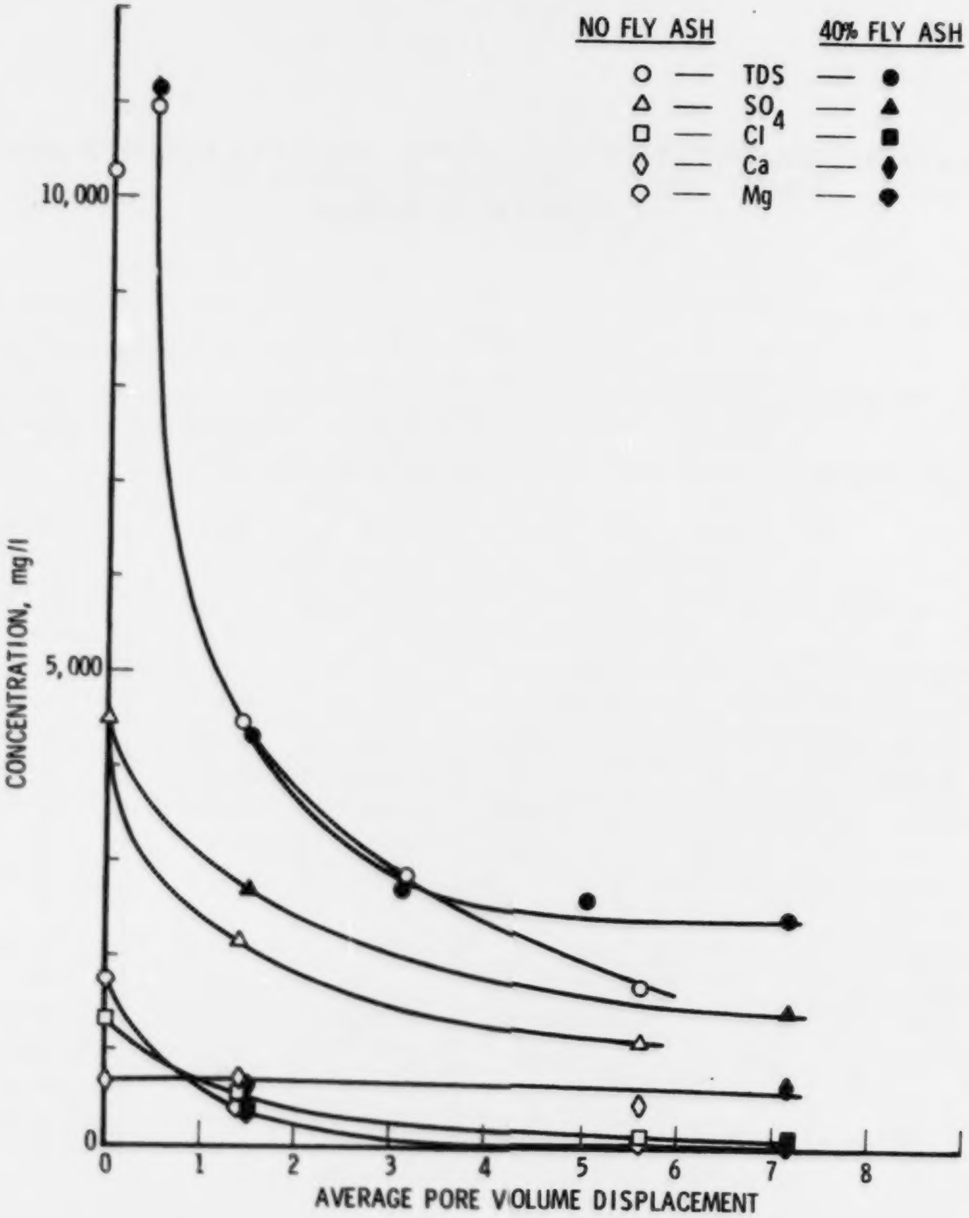


Figure 6. Concentrations of major ionic species from the TVA Shawnee lime scrubber

TABLE 9. COMPARATIVE ANALYTICAL RESULTS FOR TVA SHAWNEE LIME SLUDGE LIQUOR AND LEACHATE
Concentrations in mg/ℓ

Constituent	Without Fly Ash			Run F + 40% Fly Ash Leachate	
	9/8/76 Run F	9/8/76 Run F Leachate			
	Filtrate	First Pore Volume	Fifth Pore Volume	First Pore Volume	Seventh Pore Volume
pH	8.0	8.3	7.1	7.9	7.4
TDS	10260	4480	1770	4330	2430
Arsenic	0.058	----	0.120	----	0.360
Beryllium	<0.001	----	<0.001	----	<0.001
Boron	76	35	3	65	16
Cadmium	0.013	----	0.013	---	0.010
Calcium	650	690	450	600	640
Chromium	0.011	0.025	0.010	0.010	0.004
Copper	0.005	0.011	<0.002	<0.002	<0.002
Lead	0.010	<0.002	<0.002	<0.005	<0.005
Magnesium	1730	400	30	310	10
Mercury	<0.00006	----	0.00006	----	0.00024
Potassium	24	14	2	7	4
Selenium	0.078	----	<0.0004	----	0.051
Sodium	137	75	47	72	42
Zinc	<0.001	0.007	0.01	0.003	0.02
Chloride	1320	550	128	400	130
Fluoride	1.9	2.6	2.5	6	1.2
Sulfate	4500	2150	1100	2700	1450

TABLE 10. COMPARATIVE ANALYTICAL RESULTS FOR SCHOLZ SLUDGE LIQUOR AND LEACHATE

Concentrations in mg/ℓ

Constituent	6/20/76 Run with No Fly Ash			6/27/76 Run with Fly Ash		
	Leachate			Leachate		
	Filtrate[a]	First Pore Volume	Sixth Pore Volume	Filtrate[a]	First Pore Volume	Ninth Pore Volume
pH	12.1	12.5	12.3	12.0	10.4	9.1
TDS	155700	9140	3550	162700	17330	2140
Arsenic	---	---	<0.004	---	---	0.019
Beryllium	---	---	<0.001	---	---	<0.001
Boron	43	5	<0.5	40	<0.5	<0.5
Cadmium	---	---	0.016	---	---	0.010
Calcium	12	1000	1100	7	550	800
Chromium	---	---	0.0025	---	---	0.024
Copper	---	---	<0.002	---	---	<0.002
Lead	---	---	0.005	---	---	<0.002
Magnesium	0.1	<0.01	<0.01	0.1	0.2	0.3
Mercury	---	---	0.00030	---	---	0.00024
Potassium	320	43	1	380	74	11
Selenium	---	---	<0.0004	---	---	<0.0004
Sodium	53600	2260	12	55300	4720	82
Zinc	---	---	0.007	---	---	0.013
Chloride	5000	1070	310	4900	1050	134
Fluoride	24	48	13	4	3	0.9
Sulfate	80000	3700	1160	84000	10100	1415

[a] Incomplete analyses for filtrate samples is a consequence of insufficient sample quantity.

TABLE 11. COMPARATIVE ANALYTICAL RESULTS FOR PADDY'S RUN SLUDGE LIQUOR AND LEACHATE

Concentrations in mg/l

Constituent	Filtrate	Leachate	
		First Pore Volume	Tenth Pore Volume
pH	8.9	7.4	8.1
TDS	24230	5240	1650
Arsenic	0.011	---	0.023
Beryllium	<0.001	---	<0.001
Boron	18	2	<0.5
Cadmium	0.025	---	0.004
Calcium	515	410	260
Chromium	0.054	<0.0008	<0.0008
Copper	0.0045	0.004	<0.002
Lead	<0.005	<0.002	<0.002
Magnesium	3400	470	70
Mercury	0.00006	---	0.00006
Potassium	760	125	21
Selenium	0.0028	---	0.006
Sodium	260	40	3
Zinc	0.003	0.015	0.005
Chloride	5600	410	157
Fluoride	<1	<0.1	<0.1
Sulfate	15000	2800	920

TABLE 12. COMPARATIVE ANALYTICAL RESULTS FOR SHAWNEE LIME SCRUBBER FILTRATE LIQUORS

Concentrations in mg/ℓ

Constituent	With Fly Ash				Without Fly Ash		
	3/19/74	5/16/74	6/27/74	Run F with 40% Fly Ash[a]	8/23/76 Run E	9/8/76 Run F	
						Liquor	First PVD
pH	9.4	8.8	8.7	7.9	8.9	8.0	8.3
TDS	2800	8400	9400	4330	5650	10260	4480
Arsenic	0.15	0.01	0.02	--	<0.004	0.058	--
Beryllium	0.026	0.05	<0.002	--	<0.001	<0.001	--
Boron	--	--	46	65	9	76	35
Cadmium	0.03	0.013	0.11	--	0.025	0.013	--
Calcium	660	2420	2520	600	1450	650	690
Chromium	0.03	0.02	0.03	0.010	0.008	0.011	0.025
Copper	0.05	0.04	0.002	<0.0[illegible]	<0.003	0.005	0.011
Lead	0.01	0.13	0.33	<0.005	0.010	0.010	<0.002
Magnesium	24	200	420	310	220	1730[b]	400
Mercury	0.07	<0.05	<0.001	--	<0.00006	<0.00006	--
Potassium	11	27	28	7	22	24	14
Selenium	0.09	1.9	<0.02	--	0.022	0.078	--
Sodium	36	109	127	72	130	137	75
Zinc	0.01	0.02	0.08	0.003	0.002	<0.001	0.007
Chloride	1050	4200	4900	400	1850	1320	550
Fluoride	1.4	3.0	3.3	6	1.3	1.9	2.6
Sulfate	900	1250	800	2700	1100	4500	2150

[a] Fly ash admixed to fly ash-free sludge, first pore volume.

[b] Magnesium added to lime to evaluate absorbent efficacy.

When comparing the trace element concentration levels in samples with and without fly ash, differences exceeding 100 percent were reported as being considered significant in order to offset uncertainties resulting from analytical procedures and techniques.

Trace element concentrations are given in Table 12 for TVA Shawnee lime sludge filtrate liquors from Run E (8/23/76) and Run F (9/8/76), in which the fly ash was removed ahead of the scrubber, and from three runs made early in 1974 (Ref. 3), in which the fly ash was present and scrubbed from the flue gas. The pH of each of the liquors is in the range of 8 to 9.

The 3/19/74 sampling was taken for a starting run. The high Mg content of Run F was due to the deliberate addition of MgO to the lime as part of the TVA – Bechtel test program. Examination of Table 12 shows that with a single exception the results, for Run E and Run F, all liquors are comparable in concentration to the lowest value of the three samples that contained fly ash or, in several cases, range between the lowest and the median values for the 1974 runs. Zn appears as the single exception and is definitely lower in the Run E and Run F filtrates.

Reports of the leachate analyses (Table 9) (Ref. 3) for Shawnee Run F ash-free sludge and sludge to which 40 percent fly ash had been added showed five trace element concentrations that were greater in the sludge and ash leachate, four approximately the same in both leachates, and two higher in the ash-free sludge. Only for B and Se were the differences greater than by a factor of three. However, the As, Hg, and Zn levels in the leachate of the sludge-fly ash mixture are higher than those in the Run F filtrate liquor. Also, the last PVD of leachate showed higher Zn concentrations than the first PVD. For the greater amounts of observed Zn to be released, it was postulated that the trace element Zn is incorporated in sulfite or carbonate solid phases whose solubilities are sufficiently greater at the slightly lower pH's of the last leachate samples. A similar pattern was observed for the Zn concentrations in the leachates from the Paddy's Run sludge (Table 11). The behavior of As and Hg may also have been a consequence of their release from a solid phase during leaching.

Inasmuch as sampling of scrubber sludge containing fly ash had not been planned for the Runs E and F time period leaching tests, data from recent sludges are not available for comparing the leachate from sludges containing fly ash that was scrubbed with the flue gas and presumably was exposed to a much lower pH during the scrubbing operation. Such a comparison can be made for the leachates from the two Gulf Scholz sludge samples shown in Table 10. However, the pH range of the double alkali process used at the Gulf Scholz plant was too high to expect acid leaching of fly ash during the scrubbing operation. The high pH of the liquors (>12) causes the virtual absence of Mg, which was precipitated as the hydroxide and only began to reappear in the leachates after elution had reduced the pH to below 9. Examination of the data of Table 10 shows that of the trace elements listed, only As and Cr are found in higher concentrations in the leachate from the sample that contained fly ash. The much lower pH of the leachate sample from the Scholz sludge containing fly ash may also be responsible for the higher concentrations of these two elements. It is noteworthy that the fluoride concentrations are higher in the liquors and leachates of the ash-free sludge.

5.1.1.2.5 Effects of pH on Trace Element Solubility

Fly ash obtained from TVA Shawnee was mixed in the proportion of two parts of mechanically separated ash to one part of electrostatically separated ash to lime sludge from Run F. To this mixture, dilute HCl was added as required to maintain a constant pH. Two acid equilibrations, one at pH 4.0 and the other at pH 7.1, were continued until the pH remained constant. The mixture was then stirred for 24 hours.

The concentrations of trace elements measured in the solutions at pH 4 and pH 7 are shown in Table 13. Only the concentrations of Cd, Cu, and Pb appeared to be significantly higher in the sample at pH 4, than in the sample at pH 7. The selenium concentration was higher in the neutral sample at pH 7 than in the acidic extract. Of all the trace element concentrations measured in these fly ash tests, only the concentrations of Cd, Cu, and Pb in the sample at pH 4 were found to be significantly higher than the values for these elements measured in the sludge-fly ash leaching tests. The concentration levels of all other trace elements in the fly ash leachate were comparable to those in the sludge-fly ash extract except for the concentrations of As, which were lower than those measured in the sludge-fly ash leaching tests.

TABLE 13. TRACE ELEMENTS LEACHED FROM SHAWNEE FLY ASH AT CONTROLLED pH
Concentrations in mg/ℓ

pH	4.0	7.1
Arsenic	0.039	0.058
Beryllium	<0.001	<0.001
Cadmium	0.036	0.009
Chromium	0.006	0.009
Copper	0.036	0.003
Lead	0.022	<0.005
Mercury	0.00012	0.00015
Selenium	0.006	0.026
Sodium	10	10
Zinc	0.01	0.005

[a] Shawnee fly ash mixture of two parts mechanically separated ash and one part electrostatically separated ash.

5.1.1.3 Chemical Characteristics of Treated Waste

Since no additional leaching experiments of chemically treated waste were planned during this phase of the program, a summary of the findings provided in the first annual R&D report (Ref. 1) are summarized in the following paragraphs.

As with untreated wastes, the reduction of major species concentrations generally takes place within the first three pore volumes.

On the basis of laboratory and field test results, it was reported that the concentration of the TDS in the first pore volume of the treated leachate is approximately 50 percent of the untreated sludge leachate. After the initial flushing period of 3 to 5 pore volumes, the concentrations generally remained constant thereafter, with values from the treated wastes being approximately 25 to 50 percent of those from the untreated wastes.

The effect of chemical treatment of immobilizing trace elements is not discernible at present when compared to untreated materials because of low concentrations and significant scatter in much of the data. With additional leaching data, statistical techniques may be useful to determine the effect of chemical treatment. Also, some evidence suggests that in certain instances the additives used in the chemical treatment of FGD wastes may be contributing trace metals to the leachate.

5.1.1.4 Physical Properties

The determination of disposal, handling, and transportation techniques for FGD wastes will be strongly influenced by the physical behavior of the wastes and the resultant costs. The applicability of some disposal methods may be limited or restricted by physical properties of FGD wastes resulting from the particular state in which they are formed, i.e., water content, crystalline phase composition, and particle size and distribution. In the previous year (Table 4) (Ref. 3), experimental tests were conducted to characterize 15 FGD wastes from 7 power plant scrubbing facilities. These included pilot, prototype, and full-scale units ranging from 1- to 410-MWe capacities. In each case, the material from each facility was received as it would be for its normal state of disposal, and testing was directed toward the application of the results in landfilling and land reclamation situations.

During the period covered by this report, five additional samples from three plants (Table 4) were tested. Selected tests were also conducted on FGD wastes to which fly ash was recombined to wastes initially collected without the ash to determine the effect on physical characteristics in the event more favorable structural properties resulted from these combinations.

The physical parameters investigated included specific gravity and bulk density as a function of solids content, water retained as a result of various dewatering techniques, viscosity of slurries at various solids contents, permeability as a function of particle packing, and compactibility and load-bearing strength as a function of solids content.

5.1.1.4 Solids Characterization

The physical properties of liquid-solid mixtures are dependent upon the characteristics of both the liquid and the solid constituents as well as the interaction between them. The FGD wastes contain four principal crystalline phases: calcium sulfite, calcium sulfate, fly ash, and unreacted limestone or precipitated calcium carbonate. These solid phases exist as fine particulates suspended in an aqueous liquor which is usually saturated with ions of these solids. In addition, ions from dissolved sodium chloride or calcium chloride are also present.

The relative amounts of each of the solid crystalline phases are dependent upon many system design and operating parameters and include (1) the sulfur content of the coal and the efficiency of SO_2 removal, (2) the fly ash in the flue gas entering the scrubber and the fly ash removal efficiency of the system, (3) the stoichiometric ratio of reactants added relative to the sulfur content and the reactant utilization efficiency, and (4) the amount of oxidation of the sulfur products that takes place in the system. In addition, each crystalline phase and the characteristic of each phase will have some influence on the behavior of the waste.

5.1.1.4.2 Solids Composition

The composition of the solids fraction of each of the wastes sampled was determined by chemical means and is presented in Table 14; the analytical techniques used are described in Reference 3. The wide range in composition for each of the major solid constituents reflects the various design differences that exist among scrubber systems. Systems having high-efficiency fly ash collection facilities upstream of the scrubber are contrasted sharply with those systems having less efficient collection methods. The calcium sulfate content of the sludge reflects the tendency of the calcium sulfite to be oxidized, the oxidation usually occurring in the scrubber or reaction tank.

5.1.1.4.3 Viscosity

The viscosity of the liquid waste is a measure of its pumpability, which affects both the mode and cost of sludge transport.

The results of viscosity tests for ten sludges (Ref. 10) show that pumpable mixtures (< 20 poise) range from a high solids content of 70 percent to a low solids content of 30 percent (Figure 7).

The waste materials produced in FGD systems contain finely divided particulate materials suspended in an aqueous medium and consist of three major phases having markedly different morphologies: calcium sulfite, calcium sulfate, and fly ash. It is both the particle size distributions and phase morphologies that are believed to influence the viscosity of the sludges.

TABLE 14. PHASE COMPOSITION OF FGD WASTE SOLIDS IN WEIGHT PERCENT[a]

Atomic Formula	TVA Shawnee Limestone, 2/1/73	TVA Shawnee Limestone, 7/12/73	TVA Shawnee Limestone, 6/15/74	TVA Shawnee Lime, 3/19/74	SCE Mohave Limestone, 3/30/73	GM Parma Double Alkali, 7/17/74	APS Cholla Limestone, 4/1/74	DLC Phillips Lime, 6/17/74	UPL Gadsby Double Alkali, 8/9/74	Shawnee Lime, 9/8/76	LG&E Lime, 7/76	Gulf-Scholz, 6/20/76
$CaSO_4 \cdot 2H_2O$	21.9	15.4	31.2	6.3	84.6	48.3	17.3	19.0	63.8	19.4	15.1	15.3
$CaSO_3 \cdot 1/2H_2O$	18.5	21.4	21.8	48.8	8.0	12.9	10.8	12.9	0.2	69.2	37.4	68.1
$CaSO_4 \cdot 1/2H_2O$						19.2						
$CaCO_3$	38.7	20.2	4.5	2.5	6.3	7.7	2.5	0.2	10.8	10.3	29.5[b]	10.1
$MgSO_4 \cdot 6H_2O$	4.6	3.7	1.9	1.9								
Other							14.3[c]				3.5[d]	
$Na_2SO_4 \cdot 7H_2O$						6.9					7.8	
NaCl					1.5							
$CaSO_4$[a]									17.7			
CaS_3O_{10}[a]								9.8				
Fly Ash	20.1	40.9	40.1	40.5	3.0	7.4	58.7	59.7	8.6	<1.0	12.4[b]	<1.0
Total	103.8	101.6	99.5	100.0	103.4	101.4	103.6	101.3	101.1	98.9	101.0	97.2

[a] Phases not explicitly measured; presence deduced from x-ray study.

[b] The carbide lime used as absorbent is an acetylene manufacturing plant waste by-product, and is reported to contain 2 to 2-1/2 percent silica and 3 to 8 percent $CaCO_3$.

[c] Soluble salt, phase not determined.

[d] Carbon.

CURVE	SLUDGE	FLY ASH, %	DATE
1	GM PARMA DOUBLE ALKALI	7.4	7/18/74
2	UPL GADSBY DOUBLE ALKALI	8.6	8/9/74
3	TVA SHAWNEE LIME	40.5	3/19/74
4	DLC PHILLIPS LIME	59.7	6/17/74
5	TVA SHAWNEE LIMESTONE	20.1	2/1/73
6	TVA SHAWNEE LIMESTONE	40.1	6/15/74
7	TVA SHAWNEE LIMESTONE	40.9	7/11/73
8	SCE MOHAVE LIMESTONE	3.0	3/30/73
9	APS CHOLLA LIMESTONE	58.7	4/1/74
10	LG&E PADDY'S RUN CARBIDE LIME	12.4	7/76
11	TVA SHAWNEE LIME	<1.0	9/8/76
12	TVA SHAWNEE LIMESTONE	<1.0	9/28/76
13	GPC SCHOLZ SODA ASH DOUBLE ALKALI	<1.0	6/20/76
14	GPS SCHOLZ SODA ASH DOUBLE ALKALI	30.0	6/27/76
15	TVA SHAWNEE LIME	40.0	9/8/76

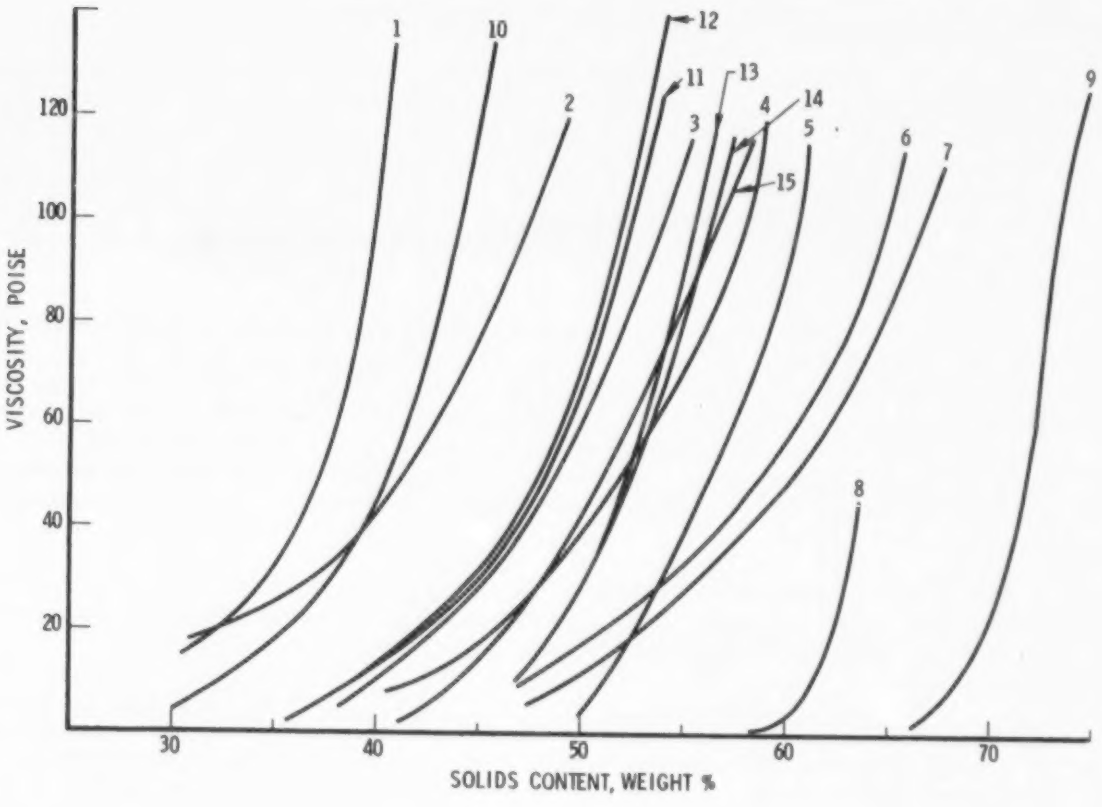


Figure 7. Viscosity of desulfurization sludges

Both calcium sulfate and calcium sulfite scrubber waste products tend to have particle sizes in the same range as fly ash, between 1 and 100 µm. However, fly ash is formed as spheres; sulfite wastes are platey or rosettes; and sulfates are blocky in shape. Unreacted precipitated $CaCO_3$ from the limestone (or lime process) is usually present in the waste and contributes an additional shape parameter.

Whereas particle shape, particularly platey sulfite particles, has been suggested as the cause of the rheological nature of sludge, in the viscous-fluid behavior of these sludges it is not apparent that the sulfite phase plays a decisive role. On the other hand, the data clearly suggest that fly ash decreases the viscosity of a sludge and high pH (of a double alkali system) increases it. Although particle shape, size, and distribution appear to influence viscosity behavior, the precise effect each may have is not clear from published results. In an instance with double alkali sludge, the results tend to suggest that agglomeration of the fine particles, rather than their presence, also affected viscosity.

Considering the lack of characterization data, the importance of experimentally determined data for system design parameters is apparent.

5.1.1.4.4 Water Retention and Wet Bulk Density

The water retention and, conversely, the dewatering characteristics of FGD wastes are important to the various disposal techniques in that they affect the volume of the disposal basin, the waste handling methods, and the condition of the wastes in their final disposal state. The water returned to the scrubbing system reduces the need for makeup water and also reduces the pollution potential associated with the liquid phase at the disposal site. Bulk density is then a consequence of the dewatering characteristics of a waste.

The effectiveness of the dewatering method and the ability of a sludge to be dewatered is a function of a number of solids characteristics, including the size and distribution of particles, and the crystalline structure of the particles, which are a function of the system as well as its operating parameters, including the type of coals. Generally, four dewatering methods are used: settling, settling by free drainage, vacuum filtration, and centrifugation. The results are almost exclusively based on laboratory experiments.

The effectiveness of a dewatering operation, i.e., the relative quantity of water that remains with the solid after performing the dewatering operation, is characterized by the wet bulk density of a sludge.

The sludges with the best overall dewatering characteristics are those with coarse particle size distributions, generally those produced by the limestone scrubber systems. The double alkali systems produce the finest particle size distributions and have the poorest dewatering characteristics.

The highest density is obtained principally by vacuum-assisted filtration in most sludges and by centrifugation in a few cases. In all cases, relatively small density differences resulted from these two dewatering methods.

In most sludges, there is very little difference in the density when dewatered by settling or settling followed by free drainage, although the latter always exhibits higher densities because of the lower retrention from its free draining condition. While free draining may not produce a significant improvement in bulk density, the slight gain coupled with its associated solids content in some cases may significantly affect its load-bearing strength (Section 4.3.2).

Generally, the wet bulk density ranges from a low of approximately 1.48 g/cm^3 (92 pcf) for settled sludges to a high of 1.76 g/cm^3 (110 pcf) for vacuum filtered (Table 15). Drained and centrifuged values were intermediate to these extremes, with the drained values being slightly higher than the settled and centrifuged slightly lower than the filtered. These values were obtained under laboratory conditions and may not be representative of results for commercial equipment use. However, it is expected that the defined trends will apply.

No general relationship has yet been determined between slurry solids content and settling rates because of the strong influence of solids morphology on this property.

An interesting phenomenon was reported (Ref. 10) with freely drained Shawnee lime sludge to which fly ash had been added. The solids content was adjusted to approximately 25 percent to simulate clarifier underflow. When poured into a test container, the coarser fly ash particles (typically 50 μm in diameter) settled more rapidly than the sulfur-phase particles (typically 20 μm) in diameter) and formed a fly ash layer on the filter paper used as a retainer. Although supernate drained through the paper as in all other cases without the fly ash layer, the presence of a fly ash layer beneath the sludge appeared to aid the dewatering process. The resultant process was nearly as effective as vacuum filtration. Because water retention in fly ash is relatively low, supernate water passes freely through the fly ash layer, creating air voids. It was postulated that, since the fly ash is contiguous with the sulfur-phase particles, surface tension forces between the fly ash particles and water are capable of overcoming the surface tension between the sulfur-phase particles and water. Thus, water is also removed from the sludge as it passes through the fly ash layer. The net consequence of this action is that more effective dewatering takes place.

5.1.1.4.5 Permeability

The pollution potential of sludge liquor into groundwaters is governed by the mobility of leaching waters, which is limited by the coefficient of permeability of the various media through which this leachate must pass.

Permeability of leaching waters through the waste defines an upper limit to the amount of leachate that enters the subsoil. The amount of liquid and the level of contamination of this liquid are jointly responsible for the pollution potential of any given waste disposal site.

TABLE 15. WATER RETENTION AND BULK DENSITY CHARACTERISTICS

Scrubber System	Dewatering Method							
	Settled		Settled and Drained		Centrifuged		Vacuum Filtered	
	Percent Solids	Density, g/cc	Percent Solids	Density, g/cc	Percent Solids	Density, g/cc	Percent Solids	Density, g/cc
Lime	40-48	1.34-1.40	43-53	1.36-1.50	50-57	1.39-1.52	56-57	1.48-1.54
Limestone	47-67	1.39-1.65	56-67	1.44-1.67	60-77	1.56-1.86	53-80	1.48-1.78
Double alkali	37-40	1.30-1.35	41-44	1.33-1.44	50-62	1.38-1.62	55-58	1.50-1.61

The permeability coefficients of untreated wastes range from 2×10^{-4} to 5×10^{-5} cm/sec (Ref. 3). The permeability coefficient of untreated sludges has been shown to be a function of the volume fraction of solids in the waste. These values are intermediate to typical values for silty sand and sandy clay, which are 10^{-4} cm/sec and 5×10^{-6} cm/sec, respecitvely. Values as low as 6×10^{-7} cm/sec have been reported for LG&E carbide-lime untreated wastes. Sludge without fly ash has been found to have permeabilities about five times greater than the sludge with fly asn, with the solids fraction nearly identical for both materials. The difference is believed to be related to agglomeration of the fine sludge particles, which respond in a manner similar to coarser materials. When fly ash replaces the sludge particles, the solids fraction does not change, but the fly ash, having a broad particle size distribution, fills pore passages such that the rate of water passage through the waste is reduced.

Consolidation of untreated wastes under pressures of 30 to 100 psi reduces the void fraction and also reduces permeability coefficients by factors of from 2 to 5 (Table 16). The higher solid volume fraction, resulting from compaction or consolidation, and the decrease in permeability

TABLE 16. PERMEABILITY COEFFICIENTS OF COMPACTED UNTREATED SLUDGE

Sludge Source	Sampling Date	Fractional Solids Volume	Permeability Coefficient cm/sec	Consolidation Pressure, psi
TVA Shawnee Lime (6% fly ash)	9/8/76	0.35 0.33	8.9×10^{-6} 1.9×10^{-5}	100 30
TVA Shawnee Lime (40% fly ash)	9/8/76	0.47 0.42 0.41	7.3×10^{-6} 1.1×10^{-5} 1.4×10^{-5}	100 30 30
LG&E (12% fly ash)	7/ /76	0.25 0.21	8.4×10^{-6} 3.4×10^{-5}	100 30
Gulf Scholz (0% fly ash)	6/20/76	0.37 0.34	1.4×10^{-4} 4.4×10^{-4}	100 30
Gulf Scholz (30% fly ash)	6/27/76	0.36 0.34	4.8×10^{-5} 8.3×10^{-5}	100 30

appear to be a function of the size of the sludge particles and the size and distribution of the fly ash particles. Consolidation of sludge at the base of a 40-foot-deep disposal site will decrease permeabilities to about 1×10^{-4} cm/sec at the surface. This value appears to represent the lower limit of untreated waste permeabilities expected in the field.

Chemical treatment tends to reduce permeability by less than a factor of 2 in some cases and several orders of magnitude in others (Figure 8).

5.1.1.4.6 Compressive and Load-Bearing Strength

The structural characteristics of wet FGD sludge affect its use where land reclamation is desired. Therefore, the load-bearing strength of the sludge is an important factor in planning for acceptable disposal of FGD waste.

Unconfined compressive strengths of untreated wastes are low, and generally no specific values are reported because the material is usually too soft to measure.

Chemically treated sludges exhibit unconfined compressive strengths ranging from approximately 25 to 4500 psi in laboratory studies. However, commercial processes being used at power stations today produce values in the range of 25 to 400 psi (Ref. 10).

Recently, load-bearing strengths as a function of the solids content of wastes dewatered by settling, with underdraining such that surface drying occurs, have been reported (Ref. 6) for a number of power plant FGD sludges (Figure 9). These results reinforce previous observations (Ref. 11) that sludges may be dewatered to critical and narrow ranges of solids content, above which the load-bearing strengths increase rapidly to values well above the minimum for safe access of personnel and equipment. However, the critical concentration appears to be unique for each waste tested, and correlation with other physical or morphological characteristics was not apparent. Field evaluations (Ref. 7) of underdrained ponds of lime and limestone sludges have shown these materials to be capable of supporting light construction equipment. Load-bearing strengths in excess of 20 psi were reached.

The development of load bearing strength of various TVA Shawnee power plant lime sludge and fly ash mixtures as a function of the time the waste was allowed to dewater by settling and with the water removed in an underdrained condition is shown in Figure 10. The strength of settled wastes without draining is also illustrated. In the latter case, low bearing strengths are exhibited even after an extended settling period. As a result of underdrainage, high strengths were developed within several days. With limestone underdrained wastes, high load bearing strengths, e.g., 12 kg/cm^2, were developed approximately 5 to 10 days after the same values were attained for lime wastes handled in a similar manner.

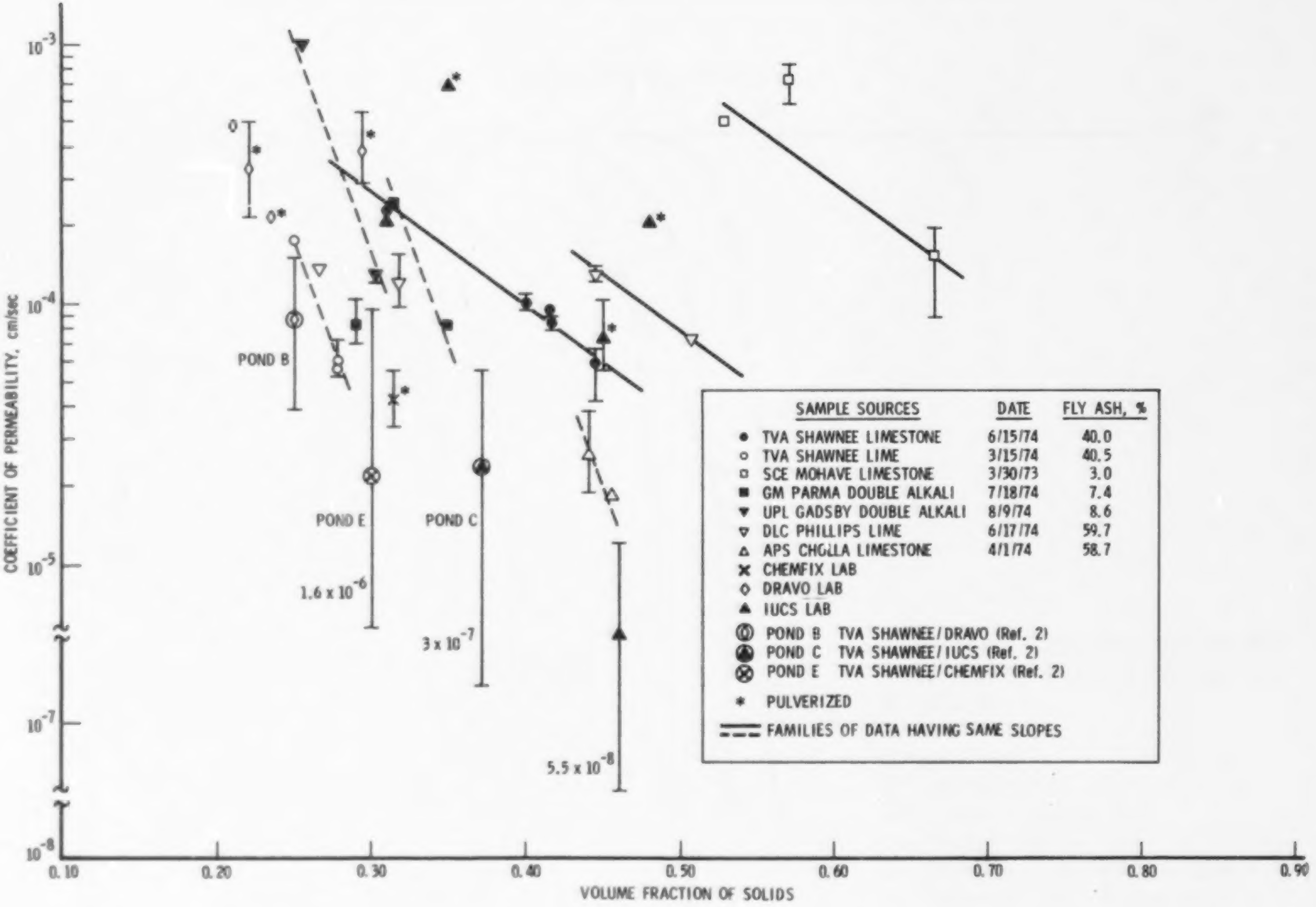


Figure 8. Permeabilities of chemically treated and untreated sludges.

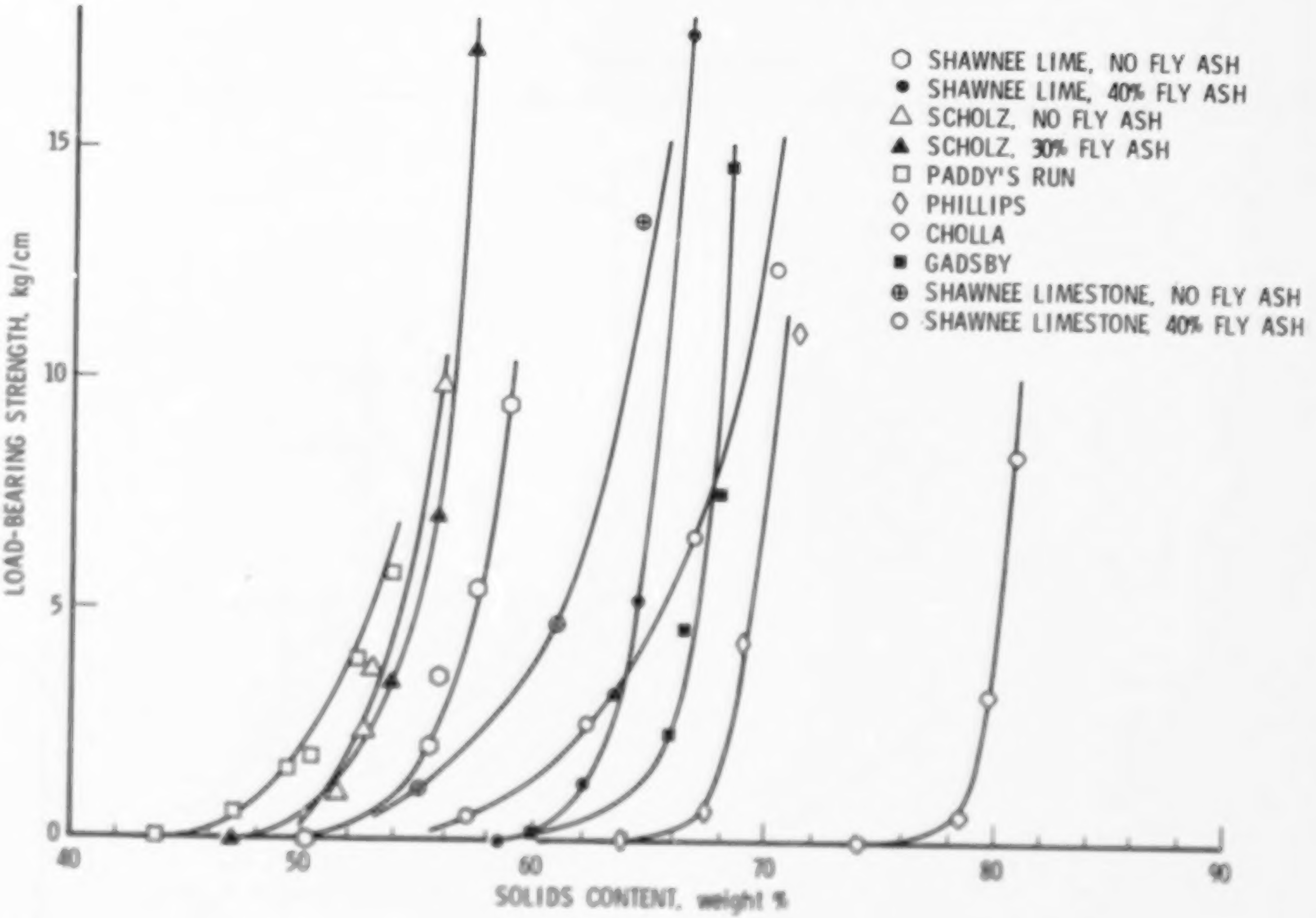


Figure 9. Compression strength of sludges and sludge/fly ash mixtures as a function of solids content.

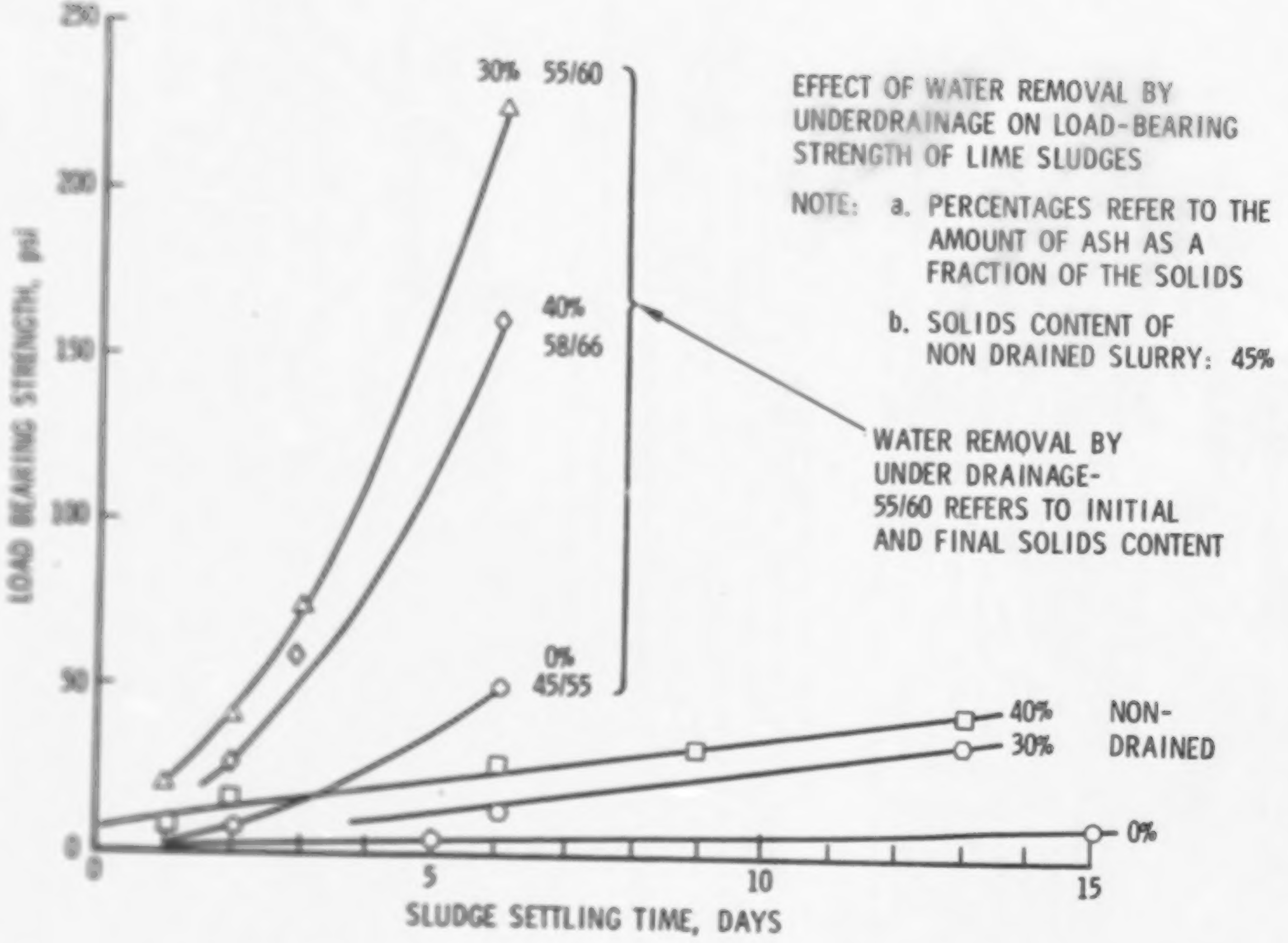


Figure 10. Effect of water removal by underdrainage on load-bearing strength of lime sludges.

The effect of rewetting dewatered wastes with the equivalent of 1/2 inch of rainfall is also reported (Ref. 6). A loss in load-bearing strength was observed. However, its recovery, when allowed to drain, appeared to be comparable to the initial buildup.

5.1.1.5 Gypsum From Forced Oxidation of RTP Pilot Plant Limestone Scrubber Sludge

R. Borgwardt of EPA, RTP, has been conducting pilot plant scale experiments evaluating the forced oxidation of sulfite sludges from the limestone and lime scrubbing of SO_2 from flue gas. The experiments were designed to determine limestone utilization, oxidation efficiency, settling rates, and bulk densities of the gypsum product. The pilot plant system consisted of a first-stage spray tower and a second-stage TCA loop (Figures 11 and 12). The first-stage loop contained a holding tank, or tower, equipped for air sparging to oxidize the sulfite. A portion of the oxidized slurry was bled off to a vacuum drum filter. Burner combustion products simulated flue gas with SO_2 and HCl being introduced into the gas stream. Fly ash was introduced, when desired, with the limestone in the second-stage loop.

To augment the numerous chemical analyses and physical property measurements being made at RTP and reported by Borgwardt (Ref. 8), Aerospace conducted additional characterization tests on filter cake and slurries from the first- and second-stage loops of samples from two runs utilizing limestone scrubbing, one with and the other without added fly ash. Scanning electron microscope (SEM) and x-ray examinations were made of crystalline phases, and wet chemical analyses were made for major constituents of both the solid and liquid phases. Also, the leaching characteristics of the solids were determined. Physical properties such as bulk densities, compressive strengths, and permeabilities were also measured on samples from the two runs.

5.1.1.5.1 Chemical and Leaching Characteristics

SEM, x-ray, and wet chemical analyses were made of the filtered solids and solids from the first- and second-stage slurries. All the measurements are in substantive agreement with each other as to the composition of the solids.

It was shown that (1) the second-stage slurry contained primarily hydrated calcium sulfite, $CaSO_3 \cdot 1/2\ H_2O$, with a small amount of gypsum; (2) both the first-stage slurry and the filtered solids were primarily gypsum with small amounts (< 1 and < 6 percent, respectively) of $CaSO_3 \cdot 1/2\ H_2O$; and (3) the filtered solids contained more $CaSO_3 \cdot 1/2\ H_2O$ than did the first-stage slurry. The presence of $CaSO_3 \cdot 1/2\ H_2O$ in the quantities observed in the filtered solids was not due to incomplete oxidation in the first stage and is not indicative of the basic characteristics process.

The presence of sulfite in the filter solids was not due to incomplete oxidation in the first-stage loop, but was determined to be the result of an unscheduled modification of the plumbing whereby a portion of

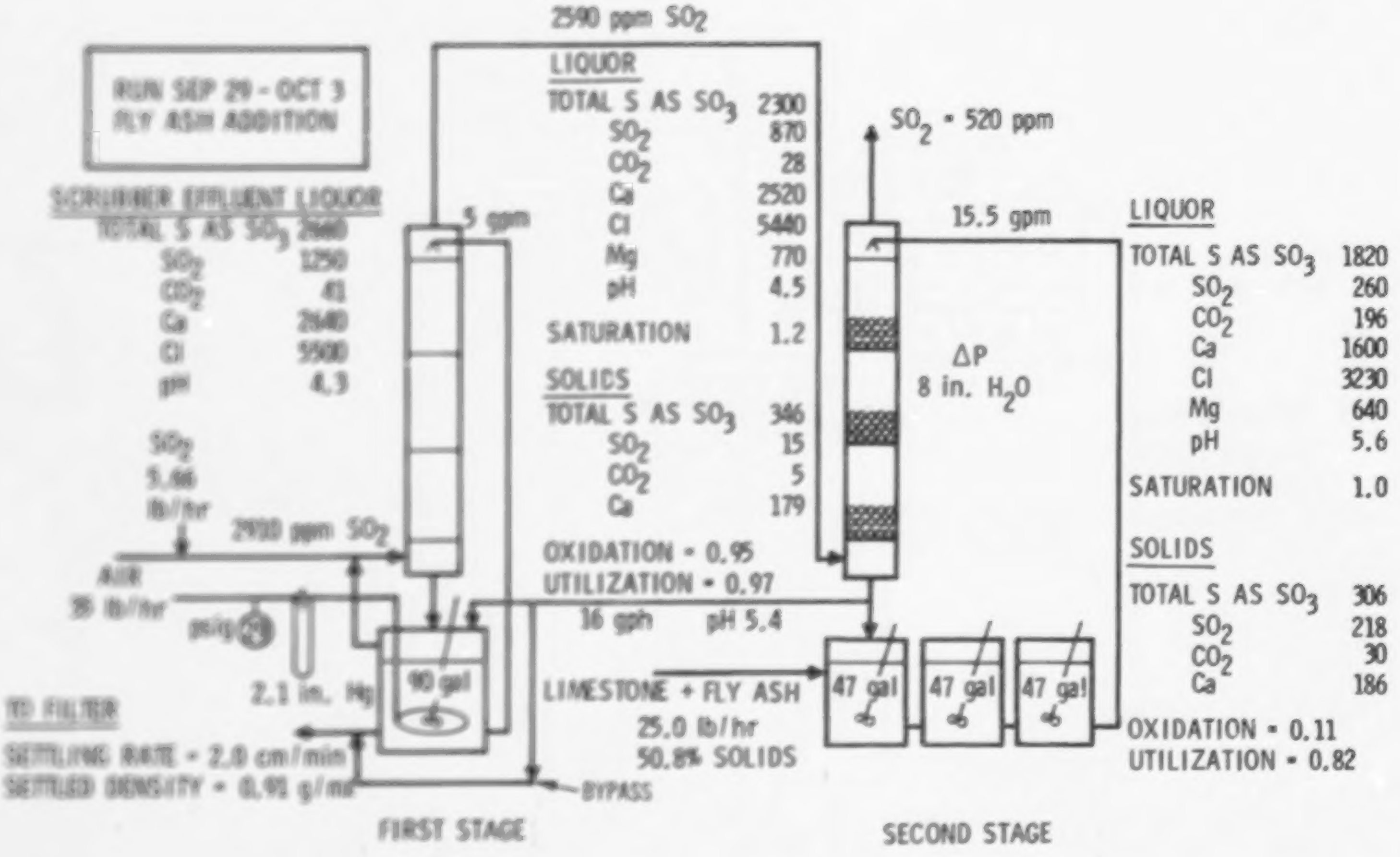
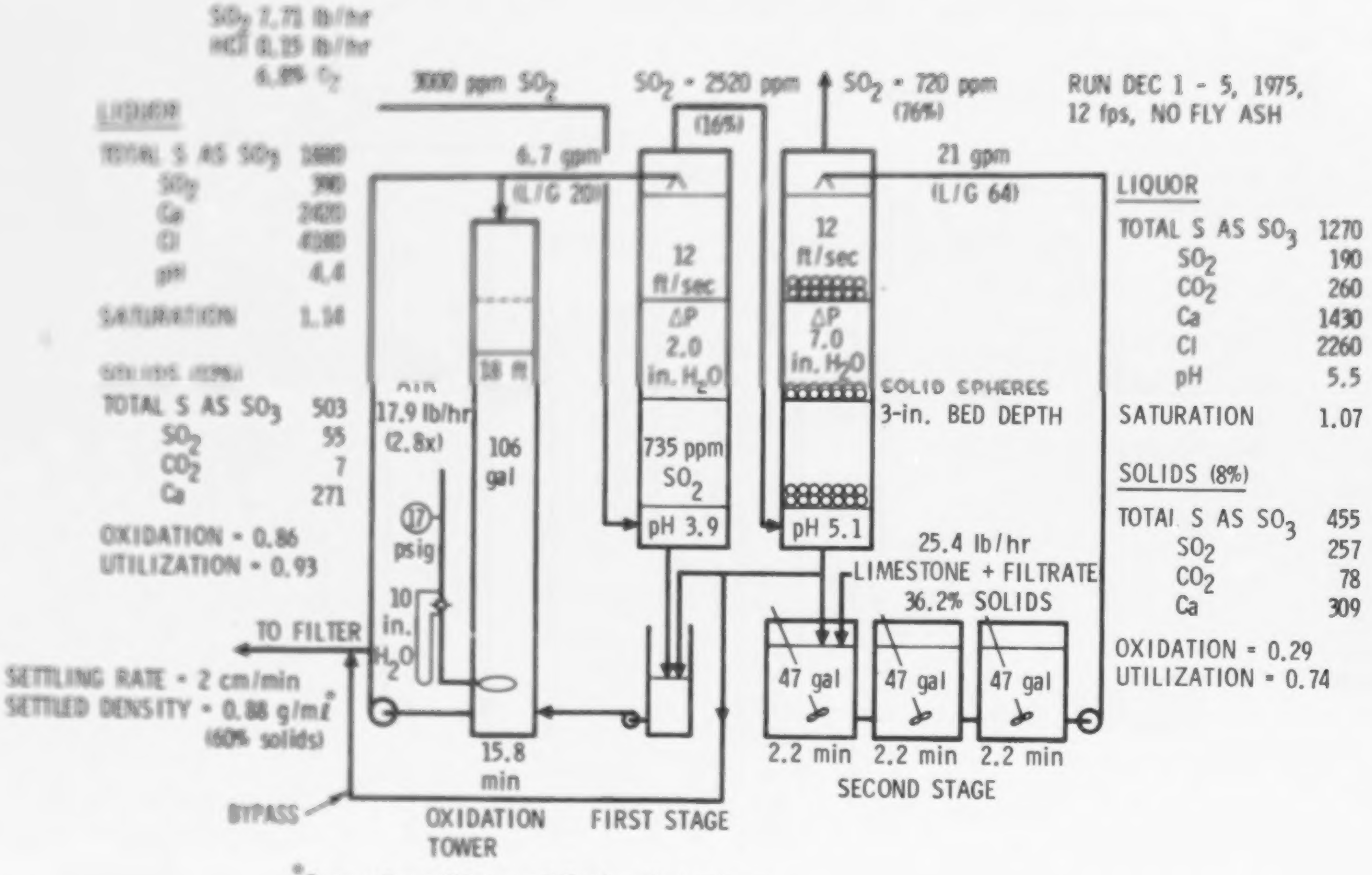

RUN SEP 29 - OCT 3
FLY ASH ADDITION
SCRUBBER EFFLUENT LIQUOR
TOTAL S AS SO3 2660
SO2 1250
CO2 41
Ca 2640
Cl 5500
pH 4.3
SO2 5.66 lb/hr
2930 ppm SO2
AIR 35 lb/hr
psig 29
2.1 in. Hg
TO FILTER
SETTLING RATE - 2.0 cm/min
SETTLED DENSITY - 0.91 g/ml
5 gpm
90 gal
BYPASS
FIRST STAGE
2590 ppm SO2
LIQUOR
TOTAL S AS SO3 2300
SO2 870
CO2 28
Ca 2520
Cl 5440
Mg 770
pH 4.5
SATURATION 1.2
SOLIDS
TOTAL S AS SO3 346
SO2 15
CO2 5
Ca 179
OXIDATION - 0.95
UTILIZATION - 0.97
16 gph
pH 5.4
LIMESTONE + FLY ASH
25.0 lb/hr
50.8% SOLIDS
SO2 - 520 ppm
15.5 gpm
ΔP
8 in. H2O
47 gal
47 gal
47 gal
SECOND STAGE
LIQUOR
TOTAL S AS SO3 1820
SO2 260
CO2 196
Ca 1600
Cl 3230
Mg 640
pH 5.6
SATURATION 1.0
SOLIDS
TOTAL S AS SO3 306
SO2 218
CO2 30
Ca 186
OXIDATION - 0.11
UTILIZATION - 0.82

Figure 11. EPA pilot plant forced oxidation system, tests with fly ash.
]



SO2 7.71 lb/hr
HCl 0.15 lb/hr
6.8% O2
LIQUOR
TOTAL S AS SO3 1880
SO2 390
Ca 2420
Cl 4380
pH 4.4
SATURATION 1.14
SOLIDS [illegible]
TOTAL S AS SO3 503
SO2 55
CO2 7
Ca 271
OXIDATION = 0.86
UTILIZATION = 0.93
TO FILTER
SETTLING RATE = 2 cm/min
SETTLED DENSITY = 0.88 g/ml*
(60% solids)
BYPASS
3000 ppm SO2
6.7 gpm
(L/G 20)
AIR
17.9 lb/hr
(2.8x)
17 psig
10 in. H2O
18 ft
106 gal
15.8 min
OXIDATION TOWER
SO2 = 2520 ppm
(16%)
12 ft/sec
ΔP 2.0 in. H2O
735 ppm SO2
pH 3.9
FIRST STAGE
SO2 = 720 ppm
(76%)
21 gpm
(L/G 64)
12 ft/sec
ΔP 7.0 in. H2O
SOLID SPHERES
3-in. BED DEPTH
pH 5.1
25.4 lb/hr
LIMESTONE + FILTRATE
36.2% SOLIDS
47 gal
47 gal
47 gal
2.2 min
2.2 min
2.2 min
SECOND STAGE
RUN DEC 1 - 5, 1975,
12 fps, NO FLY ASH
LIQUOR
TOTAL S AS SO3 1270
SO2 190
CO2 260
Ca 1430
Cl 2260
pH 5.5
SATURATION 1.07
SOLIDS (8%)
TOTAL S AS SO3 455
SO2 257
CO2 78
Ca 309
OXIDATION = 0.29
UTILIZATION = 0.74

*Grams dry solid per ml final settled volume

Figure 12. EPA pilot plant forced oxidation system , tests without fly ash.

the second-stage bypassed the first-stage loop to control the solids content in the second stage. In addition, the quantative results of the wet chemical analyses verified conclusively that complete oxidation of calcium sulfite to gypsum was achieved in the first-stage loop (Table 17).

Calcium, magnesium, chloride, sulfate, and TDS were reported for the filtrates from both samplings. The results are shown in Table 18. Mass and charge balance calculations were included; the results are expressed as ratios in Table 18. The close proximity to unity of these ratios corroborates the results of the chemical analyses. Since the analytical data appear to indicate saturation of the filtrates with gypsum, a solubility ratio was also determined. It was defined as the product of the measured calcium and sulfate ion concentrations, divided by the theoretical solubility product constant, corrected for the effect of ionic strength. These ratios also are approximately unity, also signifying gypsum saturation.

5.1.1.5.1.2 Leaching Test Results

Leaching test results of RTP limestone-scrubbed FGC gypsum wastes from sludge samples of September 30, 1975 (with fly ash) and December 4, 1975 (without fly ash) are outlined in Table 18.

Based on the drying conditions used in the TDS determination, it was reported that the $CaCl_2 \cdot 2H_2O$ in the solids was not dehydrated when the sample was brought to constant weight. A correction to reduce the TDS by the molecules of H_2O in the hydrated $CaCl_2$ was applied and reported.

The results for the filtered solids and first-stage slurries show that after two to three PVD of water have passed through the samples, gypsum, the principal ingredient of both materials, starts to dissolve and produces a leachate that is saturated with calcium and sulfate ions.

Each one of the samples of Table 18 is saturated with gypsum except for two of the second-stage slurry samples at 10 and 22 PVD whereby the gypsum supply has been essentially depleted. These two are saturated with calcium sulfite. From this point on, the calcium is supplied by the dissolution of hydrated calcium sulfite, although the anion found in the leachate will be sulfate because of the rapid oxidation of sulfite ions.

The concentrations of TDS and major constituents in leachate from the first-stage slurry samples have been plotted against pore volume displacement in Figure 13. In both samples, the TDS in the leachates reached the same minimum gypsum (saturation) value after about three PVD. The value was unchanged even when the leaching was continued until more than 30 pore volumes had been displaced. The concentrations of magnesium and chloride were reduced as leaching progressed, but sulfate remained relatively constant, and calcium was only partially removed (Table 18). The computed solubility ratios also supported the fact that each of the leachate samples was saturated with gypsum.

TABLE 17. COMPOSITION OF RTP OXIDIZED SLUDGES BY WET CHEMICAL ANALYSIS

Sample Designation	Total Solids (% of Slurry)	Composition of Solids, Percent by Weight, Dry			
		Fly Ash	$CaSO_4 \cdot 1/2\ H_2O$[a]	$CaSO_3 \cdot 1/2\ H_2O$	$CaCO_3$
Sampled 9/30/75, Contained Fly Ash					
First-Stage Slurry	11.3	40.0	62.5	<0.5	<0.5
Second-Stage Slurry	12.4	38.4	7.8	41.4	11.4
Filtered Solids	64.9	38.6	52.7	5.7	4.9
Sampled 12/4/75, Contained No Fly Ash					
First-Stage Slurry	----[b]	----	94.6	0.7	8.0
Second-Stage Slurry	----	----	11.8	51.8	37.0
Filtered Solids	----	----	86.4	9.5	----

[a] Drying process converted gypsum to $CaSO_4 \cdot 1/2\ H_2O$.

[b] ---- Not determined.

TABLE 18. ANALYSIS OF LEACHATES AND FILTRATES OF RTP FORCED OXIDATION SAMPLES

Sample/Date	Contains Fly Ash	No. of Pore Vol. Displacements	Concentration in mg/l									
			TDS	TDS Corrected[a]	Σ^b	γ^c	Ca	SO_4	Cl	Mg	Ionic Strength	Solubility Product Ratio[d]
First-Stage Slurry Solids (9-30-75)	Yes	0.7	6820	5840	5140	0.88	1300	1540	2000	300	0.15	1.16
		26.4	2180	2140	2130	0.99	550	1500	80	0.3	0.06	1.19
First-Stage Slurry Solids (12-8-75)	No	1.0	5860	4775	5110	1.07	1280	1450	2160	220	0.14	1.12
		10.3	2160	2120	1620	0.76	540	1000	80	0.04	0.05	0.92
Second-Stage Slurry Solids (9-30-75)	Yes	0.3	6770	5855	5270	0.90	950	1910	1870	540	0.16	0.97
		9.6	300	270	310	1.14	120	150	40	0.3	0.01	0.08[e]
Second-Stage Slurry Solids (12-8-75)	No	0.9	5070	4290	4290	1.00	1080	1500	1530	180	0.12	1.17
		22.1	330	300	380	1.27	100	220	60	0.3	0.01	0.10[e]
Filtered Solids (9-30-75)	Yes	0.6	7100	6010	5470	0.91	1220	1600	2220	430	0.16	1.03
		11.1	2190	2120	2065	0.97	560	1400	90	15	0.06	1.13
Filtered Solids (12-8-75)	No	0.5	10100	8100	7940	0.98	2170	1250	4040	480	0.23	0.94
		14.6	2310	2260	2100	0.93	500	1500	100	0.2	0.06	1.11
Filtrate (9-30-75)	Yes	-	9230	7595	7290	0.96	1420	1800	3330	740	0.22	0.96
Filtrate (12-8-75)	No	-	10490	8515	7750	0.91	2200	1130	3980	440	0.23	0.89

[a] Measured TDS corrected for - 2 H_2O in $CaCl_2 \cdot 2 H_2O$.

[b] Σ = sum of Ca, SO_4, Cl, Mg ions.

[c] Mass ratio: $\Sigma/TDS_{(corrected)}$.

[d] $(Ca) \times (SO_4)/K_{CaSO_4}$ with K_{CaSO_4} corrected for ionic strength.

[e] K_{CaCO_3} was used.

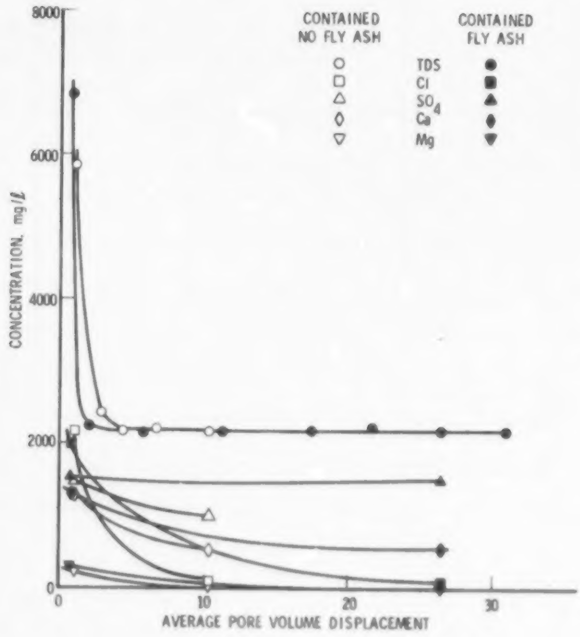


Figure 13. Concentration of major species in leachate of first-stage slurry solids of RTP oxidized sludges.

During leaching, the soluble magnesium and calcium chlorides were washed out of the bed with the residual liquor, leaving the crystalline gypsum to saturate the leaching water. The ionic strength decreased as the chlorides were removed, thus reducing the solubility of gypsum.

The results of leaching tests for the filtered solids were reported as similar to those for the first-stage slurries. The TDS leveled out at the same saturation value of about 2200 mg/ℓ .

The results shown in Figure 14 and the data of Table 18 on the leachate characteristics of the second-stage slurries illustrate the difference in composition between the second-stage and first-stage solids. The same initial pattern of changing TDS with PVD that was observed for the first-stage and filtered solids samples only persists to about five pore volumes. The TDS concentration (Figure 1), particularly the one for the sample that contained no fly ash, began to level off at the gypsum saturation content of about 2200 mg/ℓ and then decreased to about 300 mg/ℓ when 20 pore volumes were displaced. The sulfate concentrations in the final leachate samples from the second-stage slurries were about 1/10 of the amount in the final leachates of the filtered solids or the first-stage slurries.

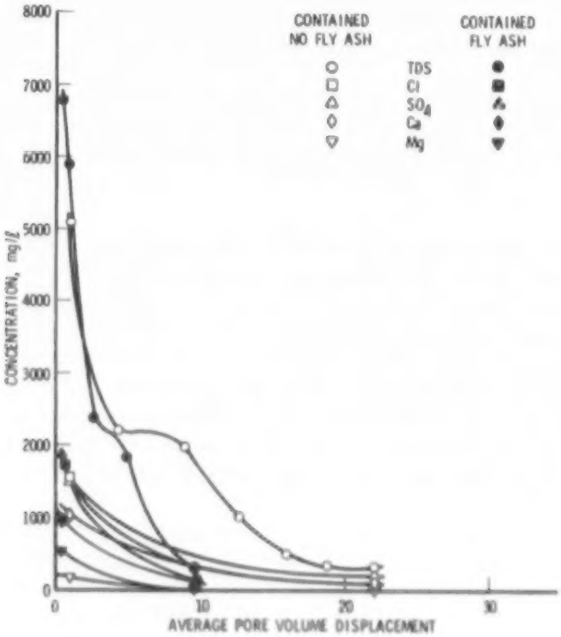


Figure 14. Concentration of major species in leachate of second-stage slurry solids of RTP oxidized sludges.

The inflection points on the TDS curves for the solids from the second-stage slurries correspond to the gypsum being depleted. Initially, the available gypsum in the leachate was beds (8 and 12 percent, Table 17) and was ultimately depleted, leaving only calcium sulfite hemihydrate. This was confirmed by x-ray diffraction measurements on the leachate bed solids made at the conclusion of the leaching tests.

In assessing the overall material balance at PVDs of less than 1.0, i.e., TDS versus Ca, SO_4, Cl, and Mg, better agreement was obtained with those samples without fly ash than with those that had fly ash in the scrubber slurry. This indicates that the major species were encompassed by Ca, SO_4, Cl, and Mg for the no fly ash case, whereas some significant additional constituents were leached when fly ash was present. It is also apparent that, after many PVDs (> 10), the concentrations of the major species were virtually the same whether or not fly ash was initially present.

5.1.1.5.2 Physical Characteristics

Measurements were made of permeability coefficients, void fraction, water retention, density, unconfined compressive strength, and load-bearing strength of fly-ash-free gypsum, calcium sulfite, and gypsum mixed with 5 to 10 percent calcium sulfite. The effects of fly ash on the properties of the various materials were also reported. A summary of the physical properties is provided in Table 19.

Permeability coefficients for the gypsum and calcium were approximately 1 × 10^{-4} cm/sec. The predominantly sulfite gypsum samples tended to be slightly higher than the 1 × 10^{-4} value and the calcium sulfite slightly lower.

The pore volume fractions of these solids range from 0.5 to 0.65 of which from 30 to 50 percent remain filled with water when the cast samples are allowed to drain and dry in the ambient air until firm enough for compressive strength measurements. For both samples, with and without added fly ash, the second-stage solids show the largest pore volume fractions (and the lowest densities), and the filtered solids retained the largest percentage of water. In all cases, the pore volume fractions of the samples which contained no fly ash were slightly higher, and their densities were somewhat lower than for the corresponding samples which contained fly ash.

A comparison of the results of unconfined compressive strength measurement for the two sets of samples (with and without fly ash) shows that when wet the corresponding solids in both sets have comparable strengths. When dry, the samples which did not contain fly ash had higher levels of unconfined compressive strength. Furthermore, for both sets of samples, the first-stage solids (gypsum) when wet showed substantially higher compressive strength than the second-stage solids (calcium sulfite). However, this difference did not persist in the first-stage solids when the samples were completely dry; the gypsum without fly ash tended to remain higher.

When the gypsum contained 5 to 10 percent calcium sulfite, the wet unconfined strength was approximately that of the sulfite. The presence of fly ash did not seem to affect the unconfined compressive strength of the drained solids. The effect of fly ash on the compressive strength of the dry solids resulted in measurably lower values than did samples without it.

Load-bearing strengths were measured on both samples of filtered solids, with and without fly ash, using an adaptation of the standard bearing ratio test for soils (ASTM D-1833-73). These gypsum samples, which contained 5 percent sulfite, exhibited strength characteristics of sludge containing typical sulfite-sulfate ratios of 3 to 4.

Measurements were repeated after further dewatering of the solids. Results for the filtered solids with and without fly ash are plotted in Figure 15. Although the measurements were terminated prematurely for the sample containing fly ash, the curves are similar for the two samples except that the rapid increase in strength with increasing solids content occurs at about 10 percent higher solids content for the sample containing fly ash.

TABLE 19. PHYSICAL CHARACTERISTICS OF RTP OXIDIZED SLUDGES

Sample Designation	Water Content, %	Density, g/cm^3 (wet)	Unconfined Compressive Strength, kg/cm^2 (wet)	Unconfined Compressive Strength, kg/cm^2 (dry)^a	Density, g/cm^3 (dry)	Pore Volume Fraction	Permeability Coefficient, cm/sec
Sampled 9/30/75, Contained Fly Ash							
First-Stage Slurry	10	1.4	4.4	0.7	1.3	0.50	1.6×10^{-4}
Second-Stage Slurry	14	1.2	1.1	0.5	1.0	0.60	8.1×10^{-5}
Filtered Solids	18	1.5	1.4	0.9	1.2	0.50	4.5×10^{-5}[b]
Sampled 12/4/75, Contained No Fly Ash							
First-Stage Slurry	15	1.3	4.2	3.0	1.1	0.55	1.1×10^{-4}
Second-Stage Slurry	14	1.0	---	1.9	0.8	0.65	9.6×10^{-5}
Filtered Solids	18	1.35	1.8	1.6	1.1	0.55	1.1×10^{-4}

[a] 50°C, vacuum.

[b] Test specimen was prepared by "rodding" slurry during initial drainage.

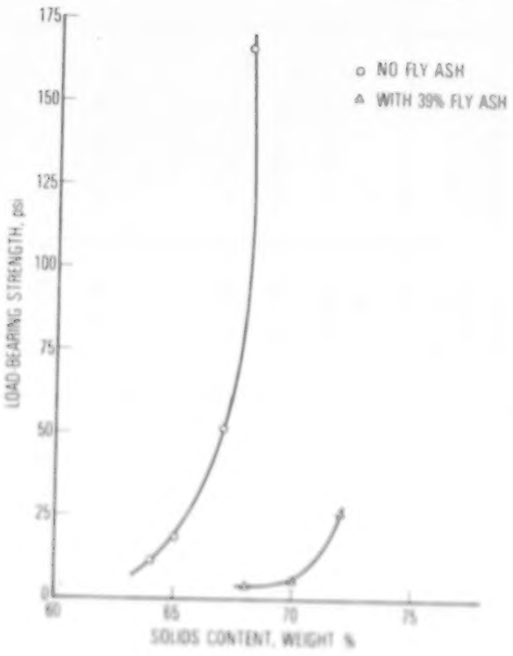


Figure 15. Load-bearing strengths of dewatered filtered solids from RTP oxidized sludges containing 5 percent sulfite.

5.1.1.5.3 Estimated Costs of Gypsum-Producing Processes

Engineering cost estimates were made for producing wallboard-grade gypsum from forced oxidation of limestone-scrubbed FGD sulfite-rich wastes (Ref. 6). Two basic processes were considered: a tail-end system incorporating an oxidation tower, which approximates the Japanese processes, and an integrated system, which represents the pilot plant installation of Borgwardt at RTP and is being tested at the TVA Shawnee plant with its 10-MWe venturi and spray tower scrubber (Figures 16 and 17). The estimates are meant to illustrate the range of costs for saleable-grade gypsum produced from SO_2 abatement processes. The costs were also evaluated for converting FGC wastes to a high gypsum content for disposal in the event that the physical and chemical properties of the gypsum and fly ash mixture were favorable for environmentally sound disposal above ground or in a landfill.

Results of the calculations indicated that, for a 500-MWe tail-end forced oxidation system, total capital costs are approximately 20 percent greater than for a base case system that included particulate removal by an electrostatic precipitator (ESP) and a limestone scrubber system producing

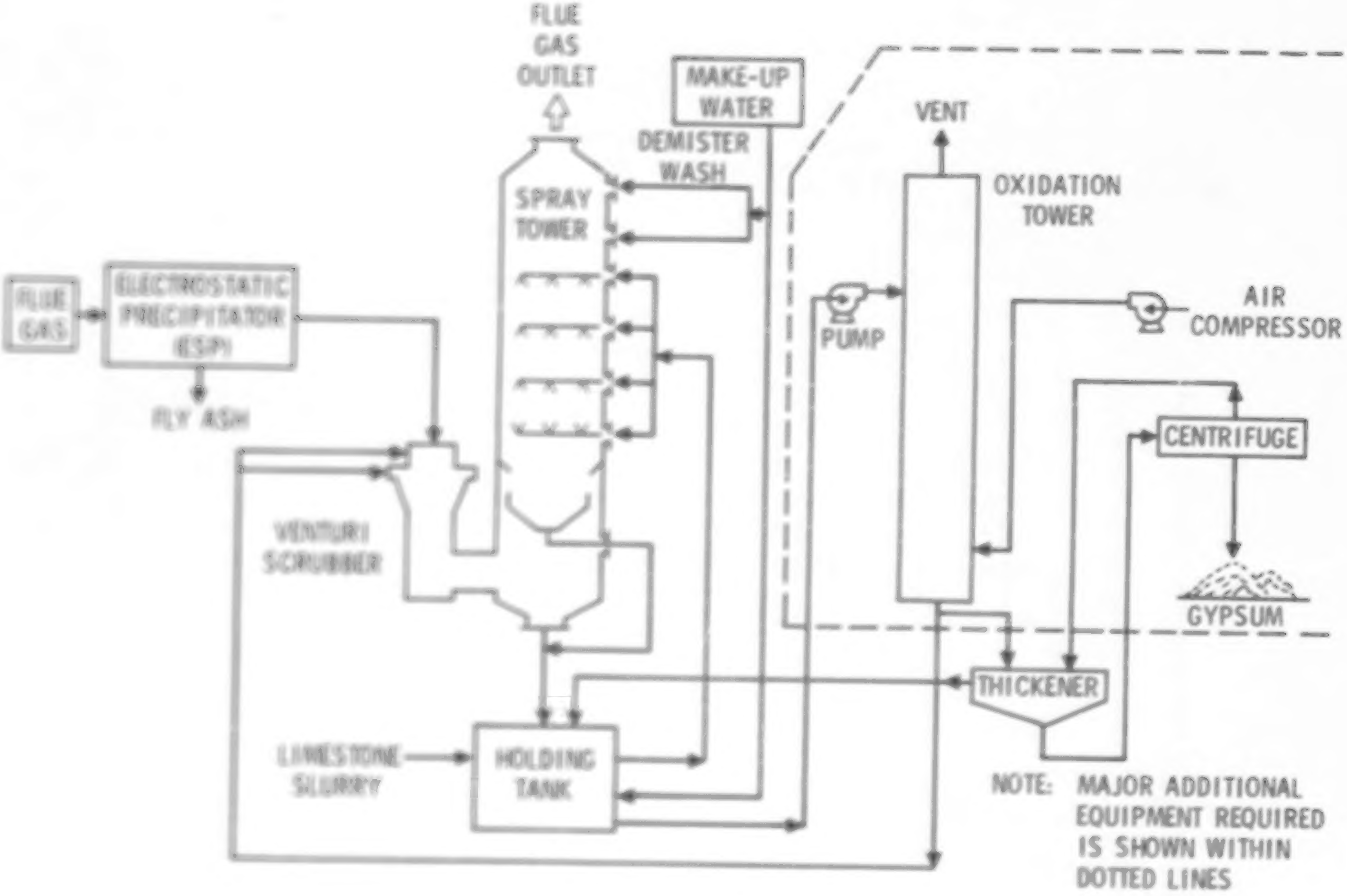

FLUE GAS OUTLET
MAKE-UP WATER
DEMISTER WASH
SPRAY TOWER
VENT
OXIDATION TOWER
FLUE GAS
ELECTROSTATIC PRECIPITATOR (ESP)
FLY ASH
PUMP
AIR COMPRESSOR
CENTRIFUGE
VENTURI SCRUBBER
GYPSUM
THICKENER
LIMESTONE SLURRY
HOLDING TANK
NOTE: MAJOR ADDITIONAL EQUIPMENT REQUIRED IS SHOWN WITHIN DOTTED LINES

Figure 16. Simplified process schematic for wet limestone tail-end scrubber forced oxidation gypsum-producing system

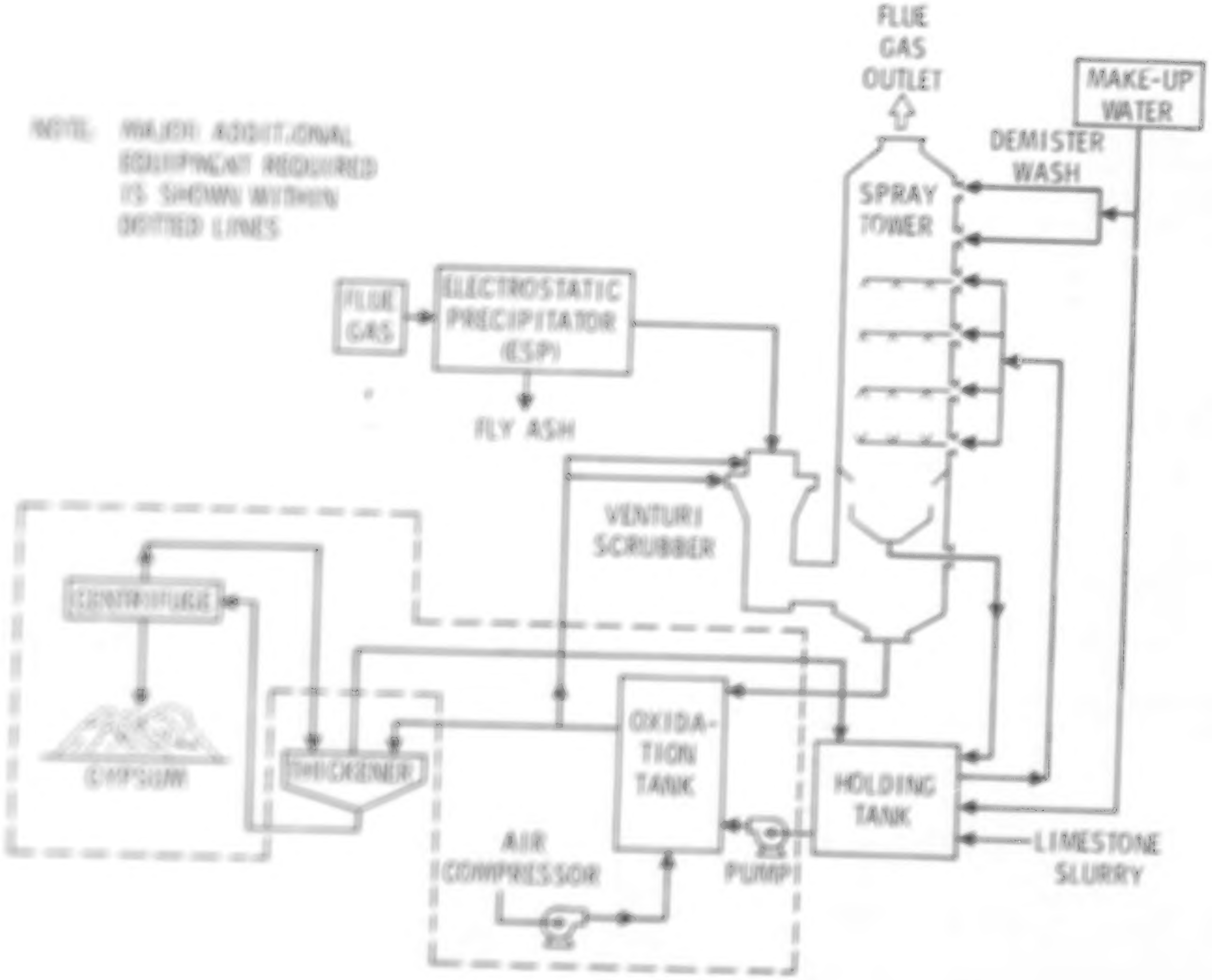

NOTE: MAJOR ADDITIONAL EQUIPMENT REQUIRED IS SHOWN WITHIN DOTTED LINES
FLUE GAS OUTLET
MAKE-UP WATER
DEMISTER WASH
SPRAY TOWER
FLUE GAS
ELECTROSTATIC PRECIPITATOR (ESP)
FLY ASH
VENTURI SCRUBBER
CENTRIFUGE
GYPSUM
THICKENER
OXIDATION TANK
HOLDING TANK
AIR COMPRESSOR
PUMP
LIMESTONE SLURRY

Figure 17. Simplified process schematic for wet limestone integrated forced oxidation gypsum-producing system.

sulfite-rich sludge, but did not include sludge disposal costs. A schematic of the basic particulate removal and scrubber system, considered as the baseline, and the major additional equipment to oxidize the sulfite-rich slurry are depicted in Figure 16. It illustrates a two-stage (venturi and spray tower) limestone wet-scrubber system, with an oxidation tower incorporated in the system to oxidize the sulfite-rich slurry to gypsum. In order to produce saleable material with a sufficiently low moisture content, centrifugation was included. Capital equipment costs for the integrated system (Figure 17) are 13 percent more than the base case scrubber (as compared to 20 percent for the tail-end system. The integrated system most nearly represents the pilot plant system tested by Borgwardt of EPA (Ref. 8) and currently being evaluated at the TVA Shawnee power plant, Paducah, Kentucky, by Bechtel and TVA at the 10-MWe level.

The operating premises and waste production data for a 500-MWe boiler are summarized in Table 20. For this estimate, the gypsum production costs were assumed to be independent of the base case scrubber system capital and annual operating costs inasmuch as gypsum modifications were estimated and reported on an incremental basis. On this basis, the effect of forced oxidation can be compared directly to the waste disposal costs by chemical treatment and landfill or by a number of other disposal options.

TABLE 20. OPERATING PREMISES FOR NEW 500-MWe SYSTEM WET LIMESTONE SCRUBBING PROCESS (1977 DOLLARS)

30 years life, 50% average operating load factor, 4380 hr/year

Coal burned: 9.6×10^5 tons/yr (3.5% S, 12% ash, 0.88 lb/kWh)

kWh generated: 21.8×10^8/yr

Dry sludge: 1.93×10^5 tons/yr (including 0.87×10^5 tons/yr fly ash)

90% SO_2 removal and 0.65 limestone utilization factor

Limestone consumption: 1.25×10^5 tons/yr

The major pieces of additional equipment required for oxidizing the sludge with the tail-end system includes oxidation towers, pumps, air compressors, and centrifuges. Individual equipment costs were taken from Reference 12 and corrected to 1977 on the basis of factors obtained from Reference 13. The total increase in costs for the these items was $\$10.14 \times 10^6$ for the tail-end system. A significant savings in equipment costs can be realized with the integrated system by use of an ion oxidation tank instead of a tower. The corresponding increase in capital equipment costs above the base case is $\$6.64 \times 10^6$.

The estimate of $10.14 × 10^6 results in a cost of $17.51 and $15.62 per ton of dry gypsum for limestone utilization factor of 0.65 and of 1.0, respectively (Table 21). It does not consider the cost incurred of disposing the waste if the sludge were not oxidized. Based on a midrange value of $9.00 per dry ton for FGC sludge chemical treatment and disposal (Ref. 14), which would offset the gypsum processing costs, and assuming a $3.00 per ton fly ash disposal cost, the net cost of producing gypsum in a tail-end systems is $6.73 and $4.84 per dry ton for the 0.65 and 1.0 utilization factors, respectively (Table 22). The effect of improved limestone utilization is highly significant in reducing the net gypsum cost. A larger effect in reducing the production cost is by considering an integrated system. With the economies resulting with that mode of operation, the estimates are $2.22 and $0.31 per dry ton, respectively, for utilization of 65 and 100 percent. Tests have shown (Ref. 8) that a utilization of virtually 100 percent can be achieved with the process.

Tests have also indicated that the settling properties of gypsum are significantly superior to that of calcium sulfite (Ref. 1). Therefore, smaller thickeners are needed for reduction of plant captial costs.

For the tail-end oxidation systems (Figure 18) and 100 percent limestone utilization, a $9 per ton chemical treatment and disposal avoidance cost results in a gypsum cost comparable to the 1975 fob price for domestic gypsum. At lower treatment costs forced oxidation costs of tail-end systems are not as favorable; at greater than $9 per ton, they become increasingly attractive. For the integrated system, the entire range of cost avoidance costs of $7 to $11 per dry ton are competitive with the mined gypsum.

In considering disposal of gypsum, informal reports have indicated the potential for better, trouble-free scrubber operation operating in a forced oxidation mode. The costs of gypsum disposal were also investigated to determine if favorable conditions existed. For instance, if for the hypothetical 500-MWe plant, an FGC sludge chemical treatment and disposal cost of $9.00 per ton of dry sludge was estimated as being needed to achieve environmentally sound disposal, oxidizing the waste to gypsum in an integrated plant would result in a cost of $6.44 per ton of dry gypsum less than chemically treating and disposing the equivalent calcium sulfite and fly ash FGC sludge that would have been produced. Since the gypsum mixture would require disposal, the $6.44 per ton can be considered the maximum gypsum (and fly ash) disposal cost that could be incurred to be equivalent to a $9.00 per dry ton FGC chemical treatment and disposal cost. For the integrated approach (Figure 19) of forced oxidation of limestone scrubber wastes, the costs of producing gypsum for sale are generally competitive with domestically mined material for limestone utilization of 65 to 100 percent and with fixation costs of $7 per dry ton or greater. If disposal is considered, the advantages are narrowed somewhat, and only the high (approximately 100 percent) limestone utilization and treatment costs of $8 per dry ton or greater become competitive if the gypsum and fly ash mixtures are disposed in a landfill or underdrained site.

TABLE 21. TOTAL INCREMENTAL COST FOR PRODUCING GYPSUM BY FORCED OXIDATION

500 MWe System, 1977 Dollars

Forced Oxidation Cost Increment	Total		Annual			
			Tail-End		Integrated	
			Utilization Factor			
	Tail-End	Integrated	0.65	1.0	0.65	1.0
Capital cost	$10.14 × 10^6	6.64 × 10^6	-	-	-	-
Annual charge @ 18%[b]	-	-	1.82 × 10^6	1.82 × 10^6	1.20 × 10^6	1.20 × 10^6
Annual labor[c]	-	-	0.58 × 10^6	0.58 × 10^6	0.58 × 10^6	0.58 × 10^6
Limestone @ $6/ton	-	-	-[d]	(0.26 × 10^6)	-[d]	(0.26 × 10^6)
Total			$ 2.40 × 10^6	$ 2.14 × 10^6	1.78 × 10^6	1.52 × 10^6
$/ton coal			2.50	2.22	1.85	1.58
Mills/kWh			1.09	0.98	0.82	0.70
$/ton dry gypsum			$17.51	$15.62	13.00	11.09

[a] Relative to wet limestone scrubbing without waste disposal, 30-year life plant, 50-percent average load factor.

[b] Reference 5.

[c] Prorated, based on scrubber system operation. Data derived from Reference 11.

[d] Included in scrubber costs. The limestone was used at 1.0 utilization factor = 81 × 10^5 tons/yr.

TABLE 22. ESTIMATED INCREMENTAL COST OF PRODUCING GYPSUM FOR SALE OR DISPOSAL RELATIVE TO THE DISPOSAL OF CHEMICALLY TREATED FGC WASTES (1977 DOLLARS)

All costs are converted to $/ton dry gypsum except as noted

	Saleable				Disposal[a]	
	Tail-End System		Integrated System		Tail-End	Integrated
	Utilization Factor					
	0.65	1.0	0.65	1.0	1.0	1.0
$/ton dry gypsum[b]	17.51	15.62	13.00	11.09	9.55	6.79
Fly ash disposal[c]	1.90	1.90	1.90	1.90	NAP	NAP
Sludge treatment and disposal cost avoidance[d]	(12.68)[e]	(12.68)	(12.68)	(12.68)	(12.68)	(12.68)
Cost avoidance, filtering	NAP[f]	NAP	NAP	NAP	(0.55)	(0.55)
Total incremental cost of gypsum per ton (dry)	6.73	4.84	2.22	0.31	(3.68)	(6.44)
$/ton coal	0.96	0.68	0.32	0.04	(0.52)	(0.90)
Mills/kWh	0.42	0.30	0.14	0.02	(0.23)	(0.40)

[a] Estimated at $9.00/ton dry sludge that would have been produced; 1.93×10^5 tons/yr total. Includes 0.86×10^5 tons/yr fly ash.

[b] Total production: 1.37×10^5 tons/yr (dry), 500 MWe plant, 30 years life, 50% average load factor, wet limestone scrubbing, forced oxidation.

[c] Estimated at $3.00/ton dry fly ash (unlined ponding).

[d] Gypsum includes 0.86×10^5 tons/yr fly ash.

[e] Parentheses denote a negative value.

[f] Not applicable.

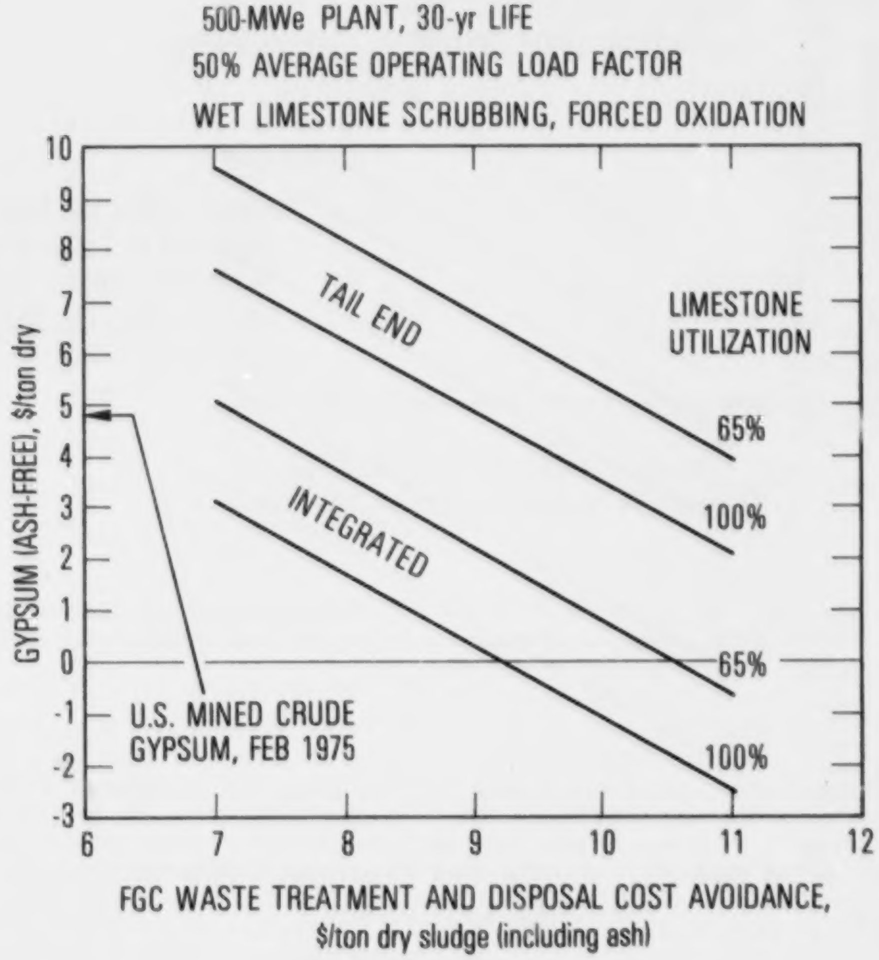


Figure 18. Cost of producing saleable gypsum as a function of sludge treatment and disposal credit (1977 dollars).

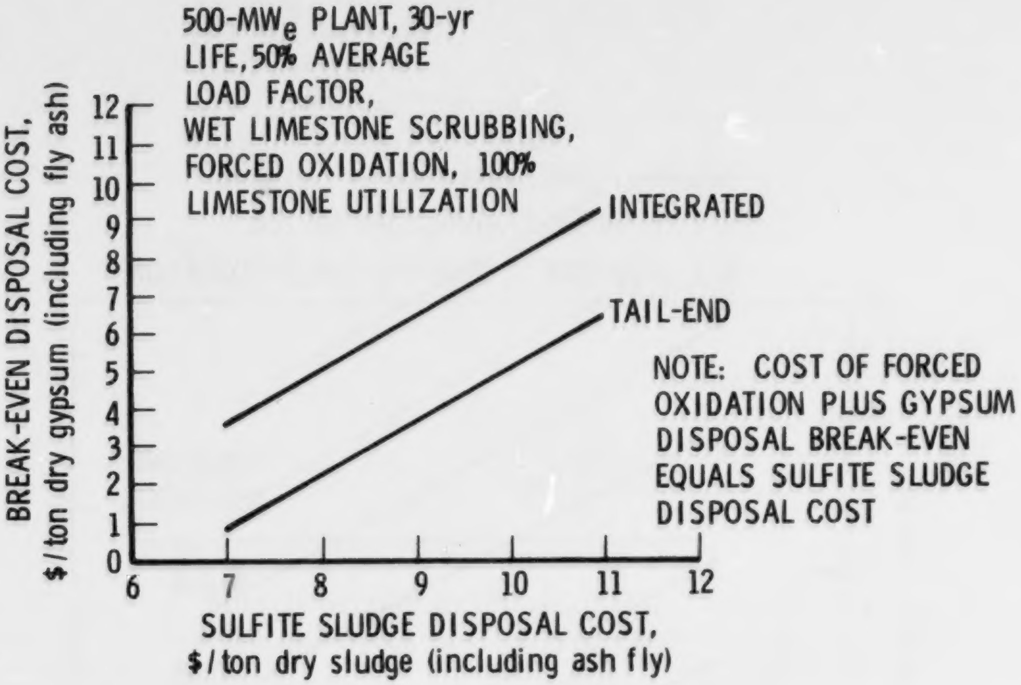


Figure 19. Disposal cost of gypsum produced by forced oxidation compared to disposal of equivalent quantity of sulfite sludge (1977 dollars).

In summary, the potential selling cost of gypsum produced in the integrated systems results in generally favorable economic trends relative to chemical treatment and disposal costs of dry waste of $7 to $11 per dry ton. An approximately $2 per ton reduction in the cost of producing the gypsum can be achieved by improving limestone utilization from 65 to 100 percent. Disposal by landfill and underdraining of gypsum and fly ash mixtures appear to be marginally competitive with fixation costs at $8 per dry ton; gypsum economics improve with increasing fixation costs.

For tail-end systems operating with 100 percent limestone utilization, gypsum production for sale is marginally competitive if fixation costs are envisioned in the $8 to $9 per ton range. Forced oxidation economics improve with increasing fixation costs. Limestone utilization of less than 90 percent tends to make this method of utilization noncompetitive with chemical treatment. The economics of disposal of gypsum and fly ash mixtures from a tail-end system do not appear to be competitive with chemical treatment.

5.1.2 Shawnee FGD Waste Disposal Field Evaluation (TVA and The Aerospace Corporation)

This project was initiated to evaluate and monitor the field site disposal of untreated and treated FGC wastes. Its purpose is to determine the effects of several scrubbing operations, waste treatment methods, disposal techniques, soil interactions, and field operation procedures. Test samples of treated and untreated wastes, groundwater, surface water, leachate, and soil cores are being analyzed in order to evaluate the environmental acceptability of current disposal technology. This program will provide a broad data base for the evaluation of controlling flue gas SO_2 by combining evaluations of scrubber performance and sludge disposal at the same site, while laboratory analyses are conducted concurrently on the same methods. Also on the basis of this program, engineering estimates of total costs (capital and operating) projected for full-scale FGD waste treatment and disposal were made (Ref. 5).

The site selected for the evaluation was the TVA Shawnee power station at Paducah, Kentucky. Two 10-MWe prototype flue gas scrubber systems, one a UOP turbulent contact absorber (TCA) and the other a Chemico venturi and spray tower. Each are capable of using lime and limestone absorbent. The wastes that they produced were placed in five disposal ponds on the plant site. Two of the ponds contain untreated wastes; each of the remaining ponds contains wastes chemically treated by one to three commercial contractors.

The Bechtel Corporation (the scrubber facility test director) provided the technical interface relating the scrubber test facility to the disposal evaluation.

The Aerospace Corporation has been providing program planning and coordination and is conducting selected chemical analyses, Data evaluation, costing estimates, and reporting are also Aerospace responsibilities. TVA has provided the on-site support relating to all pond construction and maintenance, filling of untreated ponds, and providing FGD waste for treatment. Sample collection, analysis, climatalogical and hydraulic data collection, and photographic documentation services are also performed by TVA. Chemical treatment of the waste was performed by Chemfix, Inc., Pittsburgh, Pennsylvania; Dravo Corporation, Pittsburgh, Pennsylvania; and IU Conversion Systems, Inc. (IUCS), Philadelphia, Pennyslvania.

The program began in September 1974 with the filling of the first untreated pond and is scheduled to continue through 1977. Reports on the findings from the second year and updating the first-year results have been published recently (Ref. 7). The highlights of the second-year findings are included herein. Future plans include the evaluation of untreated wastes under other disposal conditions including the disposal of gypsum.

Initially the evaluation included five sites, each occupying approximately 0.1 acre. Two of these sites contained untreated sludge, and three contained sludge that had been chemically treated. During 1976, the program was expanded to provide for the construction of three additional containments. One, an underdrained site, was filled in October 1976 with untreated lime sludge admixed with fly ash. The second, also underdrained, was filled in early 1977 with untreated limestone and fly ash waste, and the third was scheduled for filling later during 1977 with gypsum produced by forced oxidation.

In addition to plans for evaluating the environmental acceptability of the disposal of oxidized sulfite sludge (gypsum), recommendations have been made to retire an untreated pond simulating reclamation of the site. The sludge would be covered with earth and landscaped. Leachate monitoring would be continued. In addition, evaluation of runoff characteristics of a sloped treated sludge pond has been recommended to simulate a landfill. The runoff would be collected and analyzed.

5.1.2.1 Analytical Results

5.1.2.1.1 Chemical Properties

The FGD disposal field evaluation program at the Shawnee steam plant has been under way since September 1974. The program is being conducted to assess various disposal techniques and field operating procedures involving FGD sludge on the environmental quality of the disposal site. Currently, six disposal ponds are under evaluation, the sixth one having been added in 1976. Construction has been completed for two additional ponds to be filled early in 1977. A summary of the sludge types being used and data on the respective ponds are shown in Table 23.

All ponds are being monitored for leachate, supernate, and groundwater quality, and for the characteristics of the soil on the pond bottom. Sludge cores are also evaluated on those ponds containing chemically treated material. The significant results and trends observed to date are summarized in the following paragraphs.

Additional data have been acquired since the last report (Ref. 7), from the analyses of supernate, leachate, groundwater, and soil and treated material cores. Since the strength and permeability of the fixed and untreated wastes are some of the more significant of these data as they impact the environment, these results are repeated in Table 24 (Ref. 13).

A detailed analysis of the input liquor for each of the ponds is provided in Table 25.

Concentrations of the various constituents in samples taken January 21, 1976 are shown in Table 26.

Generally the TDS in the leachate from untreated ponds reached the input concentration and decreased steadily thereafter. The trends for the concentrations of TDS, SO_4, Ca, and Cl are shown in Figures 20 and 21. Minor constituents whose concentrations span a range of six orders of magnitude were relatively constant over the period monitored.

TABLE 23. POND AND FGC WASTE CHARACTERISTICS

Pond	Scrubber	Absorbent	Untreated Solids Content, Weight %	Fly Ash Solids Content, Weight %	Treatment Contractor	Fill and Treatment Date
A	Venturi-spray tower	Lime, filter cake	46	43	Untreated	Sep 24 - Oct 8, 1974
B	TCA	Limestone, clarifier underflow	38	40	Dravo	Apr 7-15, 1975
C	Venturi-spray tower	Lime, centrifuge cake	55	45	IUCS	Mar 31 - Apr 23, 1975
D	TCA	Limestone, clarifier underflow	38 38	38 38	Untreated Untreated	Oct 11-20, 1974 Jan 13 - Feb 5, 1975
E	TCA	Limestone, clarifier underflow	38	38	Chemfix	Dec 3-7, 1974
G	Venturi-spray tower	Lime, centrifuge cake	42	40[a]	Untreated	Oct 5, 1976

[a] 20 percent admixed with sludge prior to disposal, and 20 percent layered in approximately a 9:2 sludge-to-ash depth ratio.

TABLE 24. CHARACTERISTICS OF CORES FROM CHEMICALLY TREATED FGC WASTES

Sample Source and Date	Unconfined Compressive Strength, psi		Density, g/cm^3		Water Content, wt %	Estimated Fractional Pore Volume	Water Permeability, cm/sec
	Wet[a]	Dry[b]	Wet[a]	Dry[b]			
Pond E[c] 2/27/75	103 to 133	95 to 165	1.40 to 1.46	0.69 to 0.73	51.0 to 51.5	0.71 to 0.73	1.5 to 2.7 × 10^{-5}
Pond B[d] 6/12/75	27 to 33	40 to 46	1.36 to 1.44	0.59 to 0.62	56.9 to 57.8	0.75 to 0.76	6.9 × 10^{-5}
Pond C[c] 5/29/75 6/12/75	410 to 510	470 to 540	1.67 to 1.70	1.05 to 1.08	36.5 to 37.0	0.57 to 0.58	5.5 × 10^{-5} 5.5 × 10^{-7}

[a] Wet: as received.

[b] Dry: after oven drying.

[c] Samples from Ponds E and C were taken from locations free of surface water.

[d] Pond B was kept underwater continuously as in the case of disposal upstream of a dam.

TABLE 25. SHAWNEE DISPOSAL EVALUATION INPUT SLUDGE ANALYSIS RECORD

Concentrations in mg/ℓ ; solids analyses in wt%

Fill Date	Pond				
	A 10/74	B 4/75	C 4/75	D 10/74	E 12/74
Liquor Analysis:					
pH	8.3	8.9	8.9	9.2	9.4
Alkalinity	61	76	111	303	302
COD	-	140	140	130	110
Conductivity	12.0	5.3	11.1	7.1	7.1
Arsenic	0.024	0.004	0.002	-	0.004
Boron	44	97	34	93	80
Calcium	2100	1060	2720	1880	1800
Lead	-	<0.02	<0.01	<0.02	<0.01
Magnesium	290	2.5	33	50	12
Mercury	<0.0001	<0.00024	<0.00008	-	0.00033
Selenium	0.005	0.02	0.018	-	0.014
Sodium	-	17	46	56	41
Chloride	4600	1850	4700	2950	2700
Sulfate	1525	1875	1575	1500	1400
Sulfite	4	3	45	56	32
TDS	8560	5160	9240	6750	6190
Solids Analysis:					
Fly Ash	-	34.9	40.3	33.2	34.2
Calcium Carbonate	-	14.2	0	18.6	18.3
Calcium Sulfate	-	10.7	9.7	10.9	9.4
Calcium Sulfite	-	30.3	38.8	29.4	27.9
Total Solids	-	35.1	55.5	32.6	42.0
pH	8.3	8.9	8.9	9.2	9.4

TABLE 26. SHAWNEE POND LEACHATE, SAMPLED JANUARY 21, 1976

Concentrations in mg/ℓ

Constituent	Pond				
	A	B	C	D	E
Aluminum	9.2	3.0	2.6	3.8	0.2
Antimony	0.78	0.18	0.12	0.40	0.10
Arsenic	0.059	0.011	0.021	0.34	0.076
Beryllium	<0.004	<0.004	<0.004	<0.004	<0.004
Boron	45	1.3	1.0	1.3	0.5
Cadmium	0.002	<0.002	<0.002	<0.002	<0.002
Calcium	1400	525	575	675	30
Chromium	0.06	0.02	0.03	0.11	0.01
Cobalt	<0.05	<0.05	<0.05	<0.05	<0.05
Copper	<0.05	<0.05	<0.05	<0.05	<0.05
Iron	0.20	0.05	0.18	0.10	0.20
Lead	<0.01	0.01	<0.01	<0.01	<0.01
Magnesium	90	27	9	37	0.4
Manganese	0.33	0.47	0.19	<0.05	<0.05
Mercury	<0.00008	0.0007	0.0012	0.00115	0.0007
Molybdenum	2.0	0.11	0.45	0.34	0.32
Nickel	<0.05	<0.05	<0.05	<0.05	<0.05
Nitrogen	0.79	3.61	<0.010	0.74	0.52
Potassium	78	109	425	13	425
Selenium	0.014	0.009	0.022	0.004	0.005
Silicon	-	-	0.48		0.60
Silver	0.036	0.022	0.038	0.012	0.010
Sodium	66	83	143	17	540
Tin	0.32	<0.08	0.08	<0.08	0.08
Vanadium	0.08	<0.08	<0.08	0.08	0.29
Zinc	<0.05	<0.05	<0.05	<0.05	<0.05
Carbonate	< 40	<1	< 20	< 1	< 50
Chloride	2300	520	1050	970	520
Fluoride	2.9	0.05	0.4	3.0	1.75
Phosphate	<0.04	0.08	0.12	0.24	<0.04
Sulfate	1300	1100	1175	1375	1075
TDS	5860	2540	3540	2970	2640
pH	8.2	7.4	6.9	7.8	8.1

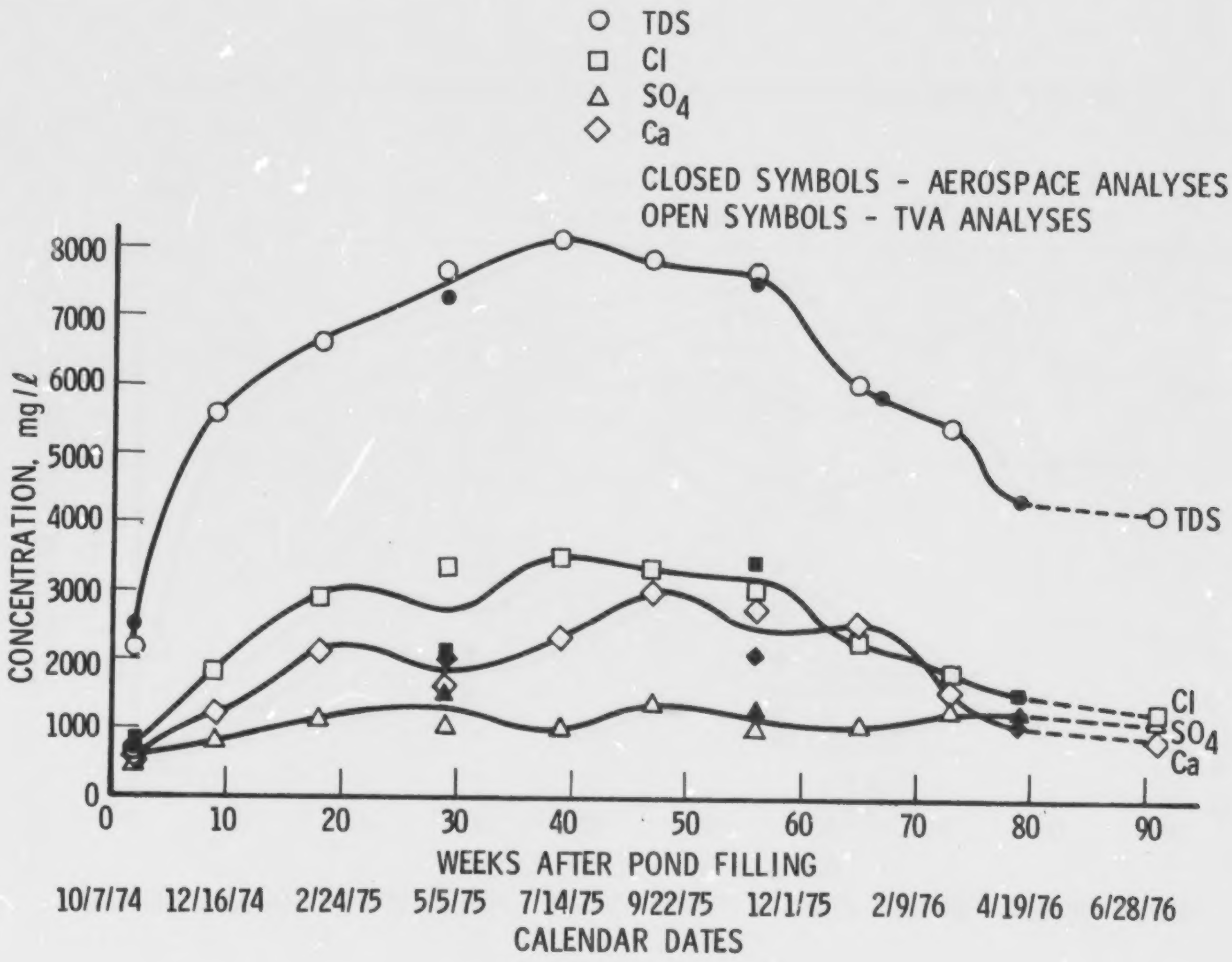


Figure 20. Concentration of TDS and major species in Pond A leachate.

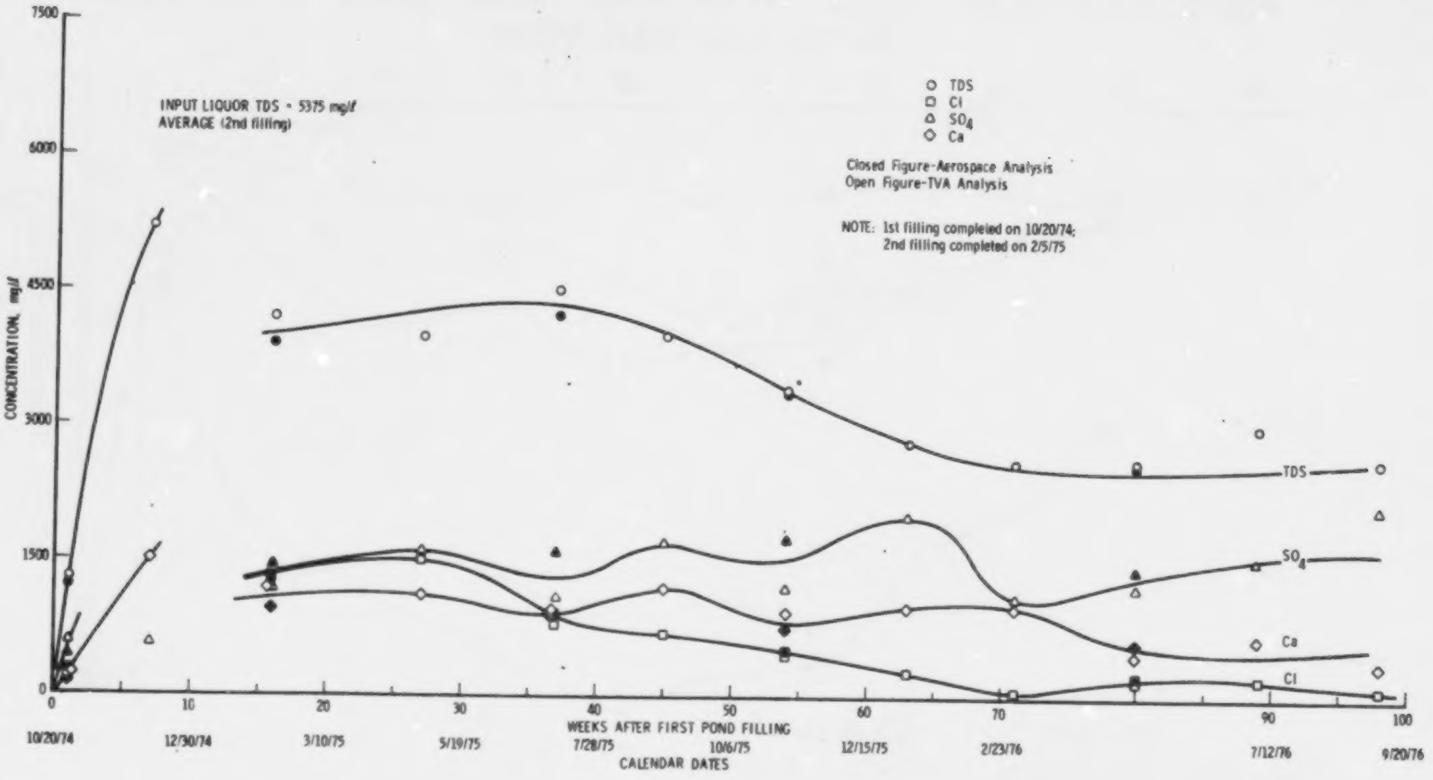


Figure 21. Concentration of TDS and major species in Pond D leachate.

The analyses of leachate from the ponds containing treated sludge show data trends similar to the untreated ponds; however, TDS levels consistently remain at a level approximately one-half that of those found in the input liquor. The results of these analyses are presented in Figures 22 through 24 for Ponds B, C, and E, respectively. Six minor constituents remained at relatively constant levels throughout the monitoring period, with the exception of the boron level in Pond C, which increased steadily to a level approaching that of the input liquor.

The TDS and the concentrations of major constituents in the supernates of the untreated ponds decreased with time from initial values corresponding to the values measured in the input liquor. After the initial decrease, fluctuations were observed in which concentrations increased during dry weather and decreased again when increased rainfall caused additional dilution.

For the treated ponds, the concentrations of major constituents and TDS in the supernate varied as a function of dry and wet weather during the monitoring period and did not exceed values of one half to two thirds of the corresponding constituent concentration in the input liquor.

The analysis of groundwater shows no indications of increases in concentration levels attributable to the ponds. For samples from the Pond A well, there is a discernible trend showing a decrease in the TDS level toward the end of the monitoring period. In the Pond D well samples, the concentrations of calcium and sulfate remained relatively constant during the monitoring period, whereas the concentration of chloride and TDS increased uniformly. The groundwater well for Pond D was monitored for 13 weeks prior to the first filling of the pond, and inasmuch as the increasing trends for chloride and TDS extend back to the beginning of the monitoring period it is not apparent that the increase is attributable to the sludge liquor of Pond D. In addition, the concentrations of chloride and TDS in the leachate of Pond D show decreasing trends during the same period.

Analysis of groundwater from wells near the treated ponds shows that the major constituents and TDS remain essentially constant over a monitoring period starting as early as 22 weeks prior to filling, and no trends attributable to the presence of the ponds have been observed.

5.1.2.1.2 Physical Properties

Physical property data on treated material from Reference 13 is presented in Table 24. The compressive strength of untreated sludge when placed in undrained ponds, such as Ponds A and D, has been too low to permit walking on its surface, i.e., less than 3 psi.

In preparation for the filling of Pond G, laboratory tests were conducted on ash-free lime filter cake (obtained from the Chemico venturi and spray tower scrubber) remixed with fly ash in a quantity representing 40 weight percent of total solids. Samples were allowed to settle or drain to obtain bearing strength measurements as a function of settling or draining time. The test results showed that undrained settling alone would not produce

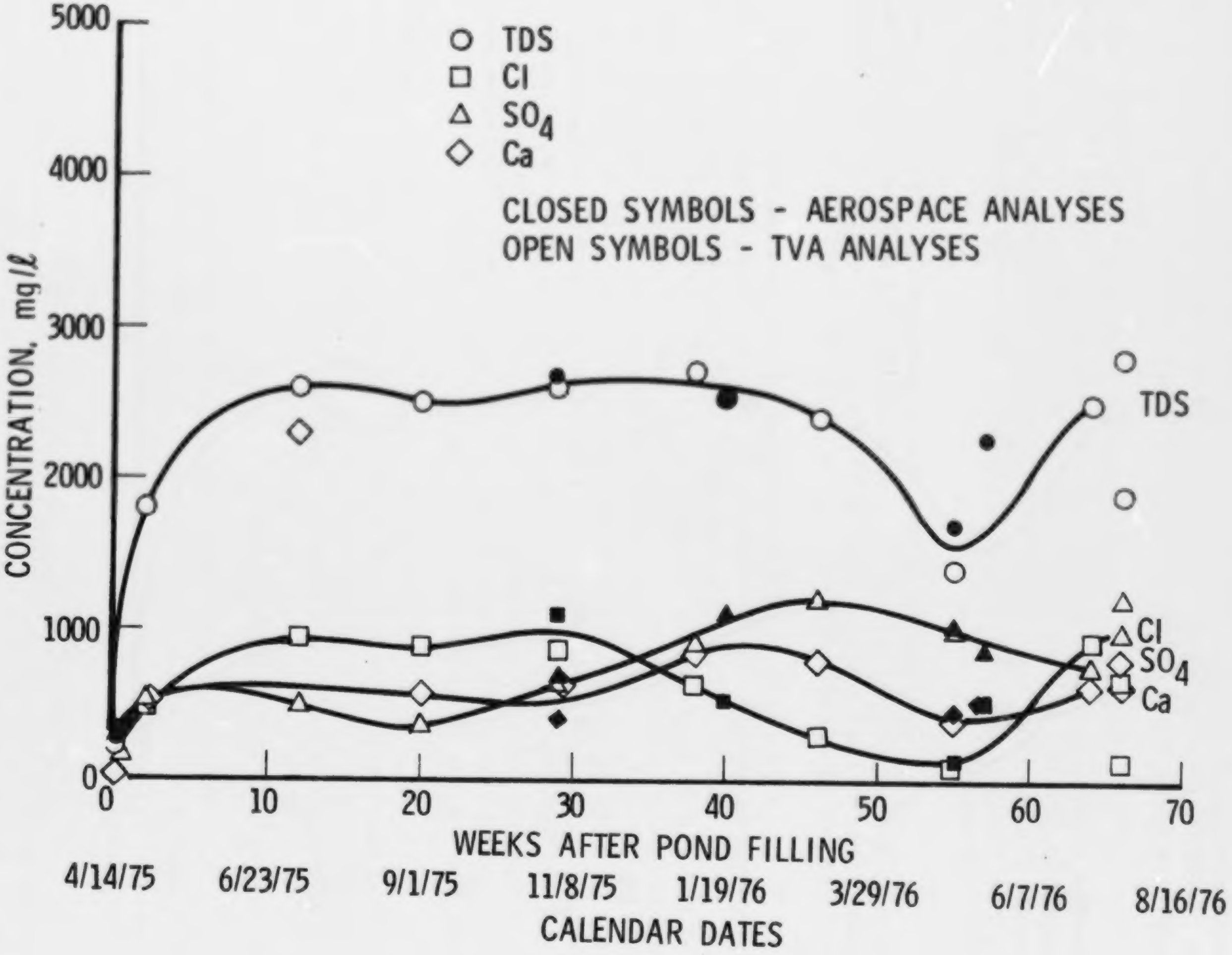


Figure 22. Concentration of TDS and major species in Pond B leachate.

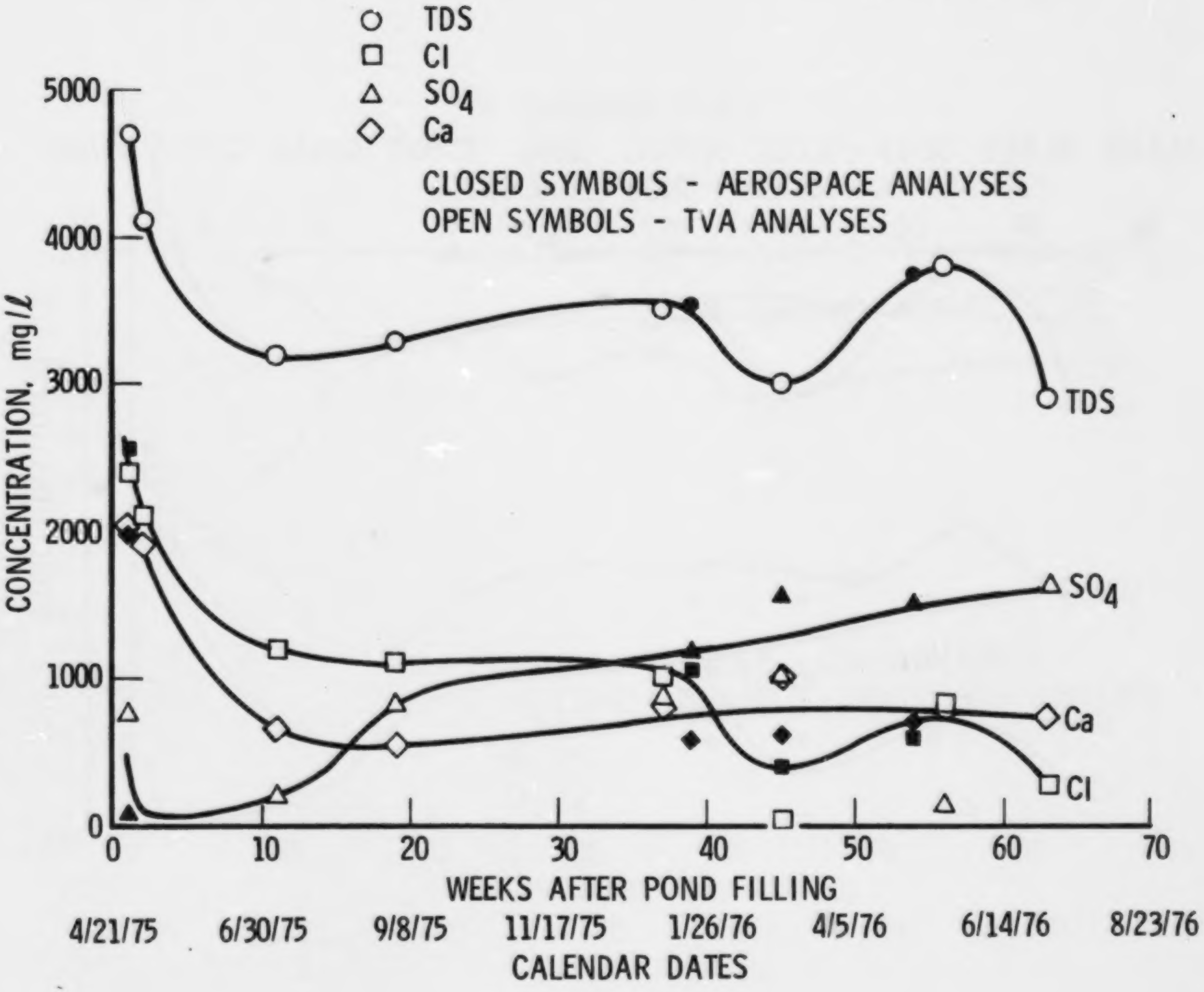


Figure 23. Concentration of TDS and major species in Pond C leachate.

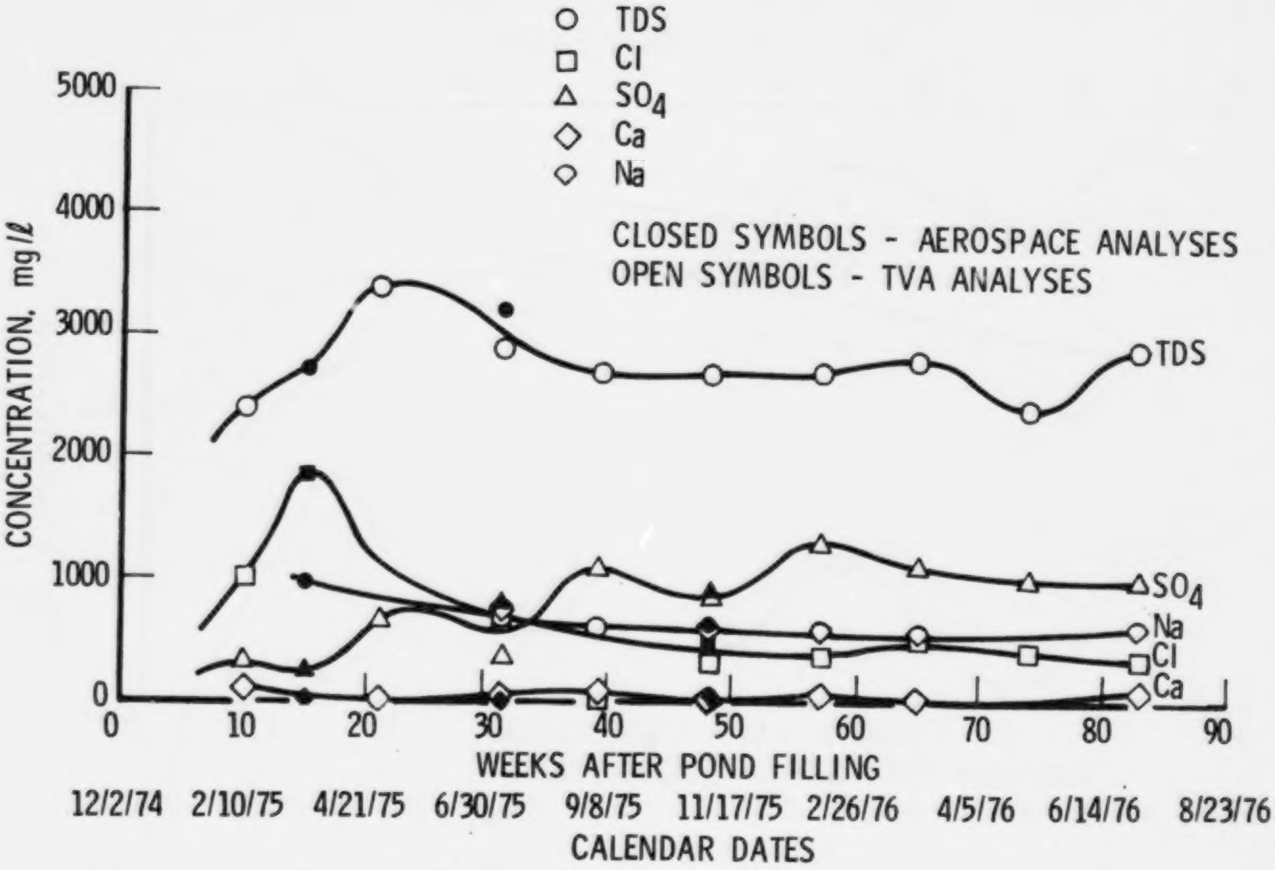


Figure 24. Concentration of TDS and major species in Pond E leachate.

bearing strengths above 40 psi after a settling time of 13 days. Samples which were allowed to drain, however, showed significant increases in bearing strength. Samples in which half the fly ash was remixed in the sludge and the other half placed in layers showed bearing strengths greater than 20 psi in 12 hours and exceeded 50 psi in 24 hours. This layered structure was selected for the filling of Pond G. During filling, personnel could walk on the surface between 2 and 10 hours after placing the sludge and fly ash in the pond. Equilibrium values of solids content and bearing strength are not available at this time but will be provided in future reports.

Soil cores were taken and tested by TVA during the construction of groundwater wells for the new ponds. The results show that the clay soil has a dry density of 1.6 to 1.8 gm/cm^3, a permeability coefficient of 10^{-6} to 10^{-8} cm/sec, and natural moisture content of 15 to 21 weight percent.

5.1.3 Laboratory and Field Evaluation of FGC Waste Treatment Processes (U.S. Army Engineer WES)

Studies are being conducted by the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, to evaluate chemical treatment (fixation) and environmental effects associated with the disposal of five FGC wastes. The program also includes evaluation of the chemical treatment of five industrial wastes. The industrial wastes are outside the scope of this report and will not be specifically discussed herein. However, the treatment and evaluation of the pollutant potential of these wastes parallels those originating in the FGC processes.

The program has been divided into three areas encompassing the following tasks:

a. Assessment of the pollution potential of the leaching of untreated and chemically fixed FGC wastes

b. Site survey and environmental assessment of existing solid waste disposal sites

c. Evaluation of existing FGC waste fixation technology

Under the first task, assessment of the pollution potential of the wastes, five chemical processes were used to treat five FGC wastes (Table 27). The processes are being evaluated by means of leaching column studies and physical and chemical testing of untreated and treated wastes. Pollution assessment leaching column experiments are scheduled for a period of two years. An interim report presenting the results of physical properties of untreated wastes after approximately eight months and treated wastes after about four months has been published (Ref. 4). A detailed summary and the test analyses conducted were provided in the first annual publication of this report (Ref. 1) and will not be repeated herein except to the extent of providing continuity for this report. During this past year, modifications were made to this task which included the addition of lysimeter testing to determine the leachability of untreated and treated FGC wastes under simulated environmental conditions and/or reduction in the number of

TABLE 27. FGC WASTE AND CHEMICAL TREATMENT MATRIX

Code No.	Type of FGC Waste	Percent Sulfur	Percent Solids	Process Designation[a]				
				A	B	E	F	G
100	Lime process, eastern coal	1.67	41.6	X	X	X	X	X
400	Limestone process, eastern coal	1.32	23.0	X	X	X	NA	X
500	Double-alkali process, eastern coal	2.00	37.0	X	X	X	NA	X
600	Limestone process, western coal	0.60	13.9	X	X	X	X	X
1000	Double-alkali process, western coal	0.46	44.2	X	X	X	NA	X

[a] X: Waste treated by processor and being tested in column
NA: Not applicable.

Processes A, B, E, F, and G include (not listed in alphabetic order):

- cement and fly ash additive,
- proprietary additive with pH adjustment,
- cement and sodium silicate additive,
- proprietary additive with pH adjustment, and
- fly ash and lime additive.

column leachate analyses. Samples will continue to be taken from the triplicate columns, but only one is expected to be analyzed, with the remaining two held in the event additional analyses are deemed necessary. Additional details are provided in Section 5.1.3.1.2.

In order to accelerate the acquisition of a data base in assessing the pollutant migration and environmental impact from FGC wastes on land disposal sites, the second task, to survey and characterize existing disposal sites, is being conducted. Its primary goal is to establish the extent of pollutant migration from existing disposal sites, the relationship to site history and disposal operations, and the establishment of site selection criteria. The geology, hydrology, and chemistry of the sites and their surrounding media will be studied. Evaluation of the site data is expected to continue for two years.

The third task of the study involves the evaluation of existing fixation technology. A list of fixation processors currently available has been compiled and their respective areas of application have been identified. Another objective is the development of a methodology for selection and application of fixation technology based on economic analysis and process evaluation. The latter includes the defintion and development of a screening test for rapid and accurate assessment of the potential environmental impact associated with the fixation and disposal of FGC wastes. The evaluation phase of this task is expected to extend over a two-year period.

5.1.3.1 Assessment of Pollution Potential of Leaching of Untreated and Chemically Fixed FGC Wastes

Five chemical treatment processes have been used with five FGC wastes (Table 27). The processes are being evaluated by means of leaching-column and physical and chemical testing of the untreated and chemically fixed wastes. The principal objectives of this task are:

a. To assess the application of fixation technology for retarding the leaching (mass transport) of pollutants from selected FGC wastes

b. To assess the leaching potential of those wastes

c. To determine the physical stability of the fixed wastes and its relationship to disposal operations

d. To evaluate the potential role of fixation of FGC wastes as a pretreatment process prior to ultimate disposal

5.1.3.1.1 Physical and Engineering Properties

Testing to characterize the untreated and fixed wastes has been completed (Ref. 4). The available physical and engineering properties are summarized in Tables 28 through 33. Physical properties describe the particle structure of the sludge, while engineering properties are used to evaluate the sludge as a mass and to predict its reaction to applied loads.

TABLE 28. COMPARISON OF SPECIFIC GRAVITIES OF UNTREATED AND TREATED FGC WASTE

Sludge	Specific Gravity					
	Untreated	Treatment Process[a]				
		A	B	E	F	G
100	2.41	2.41	2.58	2.54		2.70
400	2.51	2.47	2.35	2.55		2.49
500	2.85	2.57	2.74	2.72		2.50
600	2.53	2.52	2.57	2.57	2.46	2.41
1000	2.99	2.45	2.84	2.61		2.44

[a] Blank spaces indicate processors did not fix that sludge.

TABLE 29. PHYSICAL PROPERTIES OF TREATED SLUDGE[a]

Sludge	Specific Gravity[b]	Water Content, %	Void Ratio	Porosity, %	Bulk Unit Weight,[c] lb/ft^3	Dry Unit Weight, lb/ft^3
A-100	2.41	23.8	0.860	46.2	100.1	80.9
A-400	2.47	24.2	0.768	43.4	108.3	87.2
A-500	2.57	41.4	1.377	57.9	95.5	67.5
A-600	2.52	15.6	0.663	39.9	109.3	94.6
A-1000	2.45	23.7	0.958	48.9	96.6	78.1
B-100	2.58	77.5	2.711	73.1	77.0	43.4
B-400	2.35	69.5	1.794	64.2	89.0	52.5
B-500	2.74	67.3	2.150	68.3	90.8	54.3
B-600	2.57	88.9	2.811	73.8	79.6	42.1
B-1000	2.84	70.9	2.717	73.1	81.5	47.7
E-100	2.54	6.4	0.671	40.2	101.1	94.9
E-400	2.55	8.7	1.072	52.2	82.7	76.1
E-500	2.72	6.5	0.822	45.1	99.3	93.2
E-600	2.57	10.7	0.601	37.5	110.9	100.2
E-1000	2.61	0.7	0.987	49.7	82.7	82.0
F-600	2.46	3.7	0.996	49.1	81.0	78.1
G-100	2.70					
G-400	2.49	10.7	1.737	63.5	62.7	56.8
G-500	2.50	7.6	2.198	68.7	52.5	48.8
G-600	2.41	13.3	1.991	66.6	56.9	50.3
G-1000	2.44	17.0	1.617	61.8	68.1	58.2

[a] Tests conducted using 60°C oven for drying.

[b] Value determined using one sample; all others are average for three samples.

[c] Sample air-dried prior to determination of unit weight.

TABLE 30. PERMEABILITY TEST DATA FOR UNTREATED SLUDGE

Sludge	Solids, %	Water Content,[a, b] %	Dry Unit Weight,[a] lb/ft^3	Void Ratio	Coefficient of Permeability, cm/sec
R-100	54.8	82.5	58.8	1.559	3.610×10^{-5}
	63.1	58.6	64.4	1.336	1.070×10^{-5}
R-400	51.1	95.7	57.9	1.706	9.498×10^{-5}
	59.8	67.0	70.1	1.235	7.784×10^{-6}
R-500	59.2	145.6	30.3	4.872	4.373×10^{-5}
	45.0	121.6	36.0	3.942	2.505×10^{-5}
R-600	69.9	43.0	86.9	0.818	2.013×10^{-5}
	77.5	29.4	103.6	0.525	1.439×10^{-5}
R-900	43.9	128.2	46.8	2.682	3.524×10^{-5}
	50.3	98.7	53.1	2.245	2.834×10^{-5}
R-1000	40.5	146.5	43.2	3.321	8.461×10^{-5}
	42.4	136.1	48.9	2.817	6.536×10^{-5}

[a] All drying done in 60°C oven. Note two sets of data for each sludge.

[b] Dry weight basis.

[c] Corrected for water at 20°C.

TABLE 31. PERMEABILITY TEST DATA FOR TREATED SLUDGE

Sludge	Solids, %	Water Content,[a, b] %	Dry Unit Weight,[a] lb/ft^3	Void Ratio	Coefficient of Permeability,[c] cm/sec
A-100	78.1	28.3	76.9	0.956	2.057×10^{-6}
A-500	67.6	47.8	62.3	1.575	1.124×10^{-7}
A-600	86.2	16.1	92.5	0.701	4.308×10^{-7}
A-900	83.3	19.5	68.0	1.369	3.847×10^{-5}
A-1000	78.1	27.8	73.7	1.075	8.953×10^{-7}
B-100	82.0	21.9	60.0	1.684	1.590×10^{-4}[d]
B-400	82.6	21.2	63.7	1.303	1.082×10^{-5}
B-500	65.4	52.7	54.2	2.156	4.563×10^{-5}
B-600	59.2	68.8	44.4	2.613	3.968×10^{-5}
B-1000	58.1	71.9	45.1	2.931	6.625×10^{-5}
E-100	77.0	30.9	81.0	0.958	7.935×10^{-4}[d]
E-400	91.0	11.3	72.5	1.196	2.518×10^{-6}
E-500	75.2	33.4	77.9	1.180	4.540×10^{-11}
E-600	80.0	24.7	88.3	0.881	3.571×10^{-8}
E-1000	90.1	10.4	77.3	1.108	7.328×10^{-7}
F-600	97.0	3.7	78.1	0.966	5.007×10^{-6}
G-400	93.5	7.7	53.1	1.927	5.241×10^{-5}
G-500	98.4	2.9	50.6	2.084	1.388×10^{-4}[d]
G-600	91.7	9.1	53.0	1.837	1.224×10^{-4}[d]
G-1000	63.7	56.8	54.0	1.821	4.047×10^{-5}

[a] All drying done in 60°C oven.

[b] Dry weight basis.

[c] Corrected for water at 20°C.

[d] Value questionable because flow restriction caused by sample support may have influenced flow through sample.

TABLE 32. UNCONFINED COMPRESSION TEST DATA FOR TREATED SLUDGE

Sludge	Initial Dry Unit Weight lb/ft^3	Undrained Shear Strength,[a] lb/in^2	Unconfined Compressive Strength, lb/in^2	Modulus of Elasticity, lb/in^2
A-100	80.9		100	1.10×10^4
A-500	67.6		188	3.03×10^4
A-600	94.6		403	7.50×10^4
A-1000	78.1		337	1.10×10^5
B-100	41.7	11.85	23	3.57×10^3
B-400	65.4	22.28	44	3.64×10^3
B-500	58.3	21.37	43	1.00×10^4
B-600	44.2	17.66	35	3.39×10^3
B-1000	53.5	11.62	23	1.10×10^3
E-100	95.0		2574	4.50×10^5
E-400	82.7		719	1.26×10^5
E-500	93.3		2200	3.10×10^5
E-600	100.3		4486	1.67×10^6
E-1000	82.7		1374	2.45×10^5
F-600	69.6		396	5.00×10^4
G-400	56.8		242	9.10×10^4
G-500	48.8		86	1.59×10^4
G-600	50.3		126	1.64×10^4
G-1000	58.2		144	5.28×10^4

[a] Taken as one-half unconfined compressive strength. Significant for soil-like sludges only. Blank spaces indicate nonsoil-like sludges.

TABLE 33. CHANGES IN DRY UNIT WEIGHT AFTER COMPACTION OF SLUDGES TREATED BY PROCESS B

Sludge	Dry Unit Weight[a]			
	Without Compaction, lb/ft^3	Maximum after Compaction,[b] lb/ft^3	Change due to Compaction, lb/ft^3	Optimum Moisture Content, %
B-100	43.4	42.9	-0.5	82.5
B-400	52.5	56.9	+4.4	47.0
B-500	54.3	51.5	-2.8	65.0
B-600	42.1	41.9	-0.2	89.5
B-1000	47.7	50.5	+2.8	73.5

[a] Drying performed in 60°C oven.

[b] 15-blow compaction test; 7400 ft-lb/ft^3 compactive effort.

The approach taken by WES was to characterize the wastes by evaluation of their physical and engineering properties as determined by standard tests and procedures applied to soils. In addition to assessing the effects of the fixation process by evaluating the change in properties resulting from fixation, characterization may be possible by comparison of results with typical values of familiar materials such as soil-cement, concrete, and soils.

5.1.3.1.1.1 Untreated Wastes

In comparison with soils, the untreated FGC sludges are generally of low density and low water content. The specific gravities, however, are comparable to soils, indicating that structural rearrangement of the particles are expected to result in densities of the same magnitude as those of soils. The high porosities of the sludges give an indication of the loosely packed nature of the sludges; the total volume of most samples exceeded 50 percent voids.

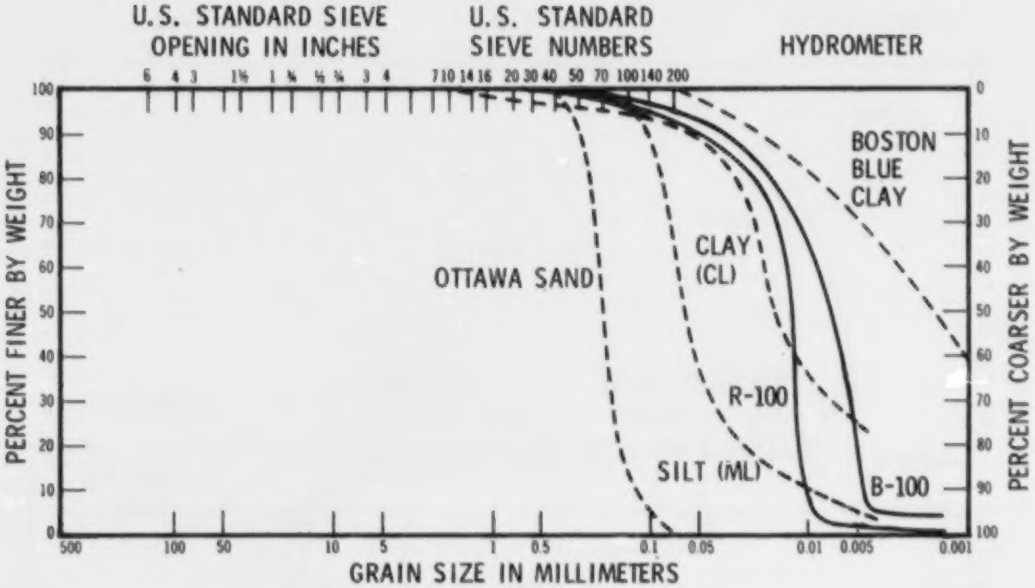
On the basis of the grain size distribution (Figure 25), the sludges were classified as silt (ML) under the Unified Soil Classification System (USCS) and as silt and silt loam under the U.S. Department of Agriculture (USDA) system. On this basis, general characteristics were predicted. The untreated sludges contain a high percentage of particles that pass the number 200 sieve, which is usually indicative of low permeability, $< 10^{-4}$cm/sec. Strength is also expected to be low. Soils of low density are generally so loosely packed that little intergranular friction is developed, and shear strengths are correspondingly low in the absence of cementation.

Prior to treatment, sludges were characterized by low densities and low water content, leading to the anticipation of low shear strength (2 to 8 psi) and low permeability ($< 10^{-4}$cm/sec). Porosity is high, and improvement in the quality of the sludges should be accomplished by restructuring the particle matrix to provide a tighter packing arrangement. Comparison of the physical properties of the untreated sludges to soils is presented in Table 28.

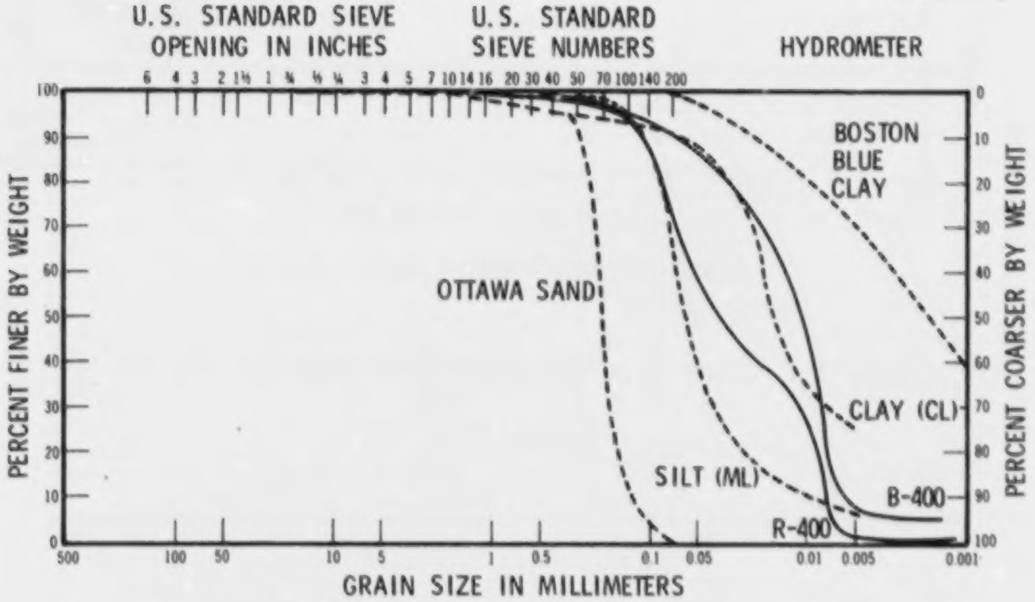
5.1.3.1.1.2 Treated Wastes

The grain size distribution of nine sludges treated by Process B and of one sample treated by Process F were determined and reported (Ref. 4). The treated wastes exhibited characteristics similar to silt (ML) and silty sand (SM) based on the USCS system. Sludges fixed by Process B were classified as loam or as fine sandy loam under the USDA system. Grain size distribution curves illustrating the effects of Processes B and F on a limestone sludge from a plant using Western coal is shown in Figure 26.

A comparison of the grain size curves for sludges treated with Process B with those of untreated sludges shows that the process had little effect on the particle size distribution. Particle sizes of the fixed sludges were essentially in the same range as those of the untreated sludges. The slight change in gradation for B-treated wastes was not uniform for all sludges. All B-treated sludges were reported to remain similar to the untreated sludges in texture and were considered similar to silty soils.

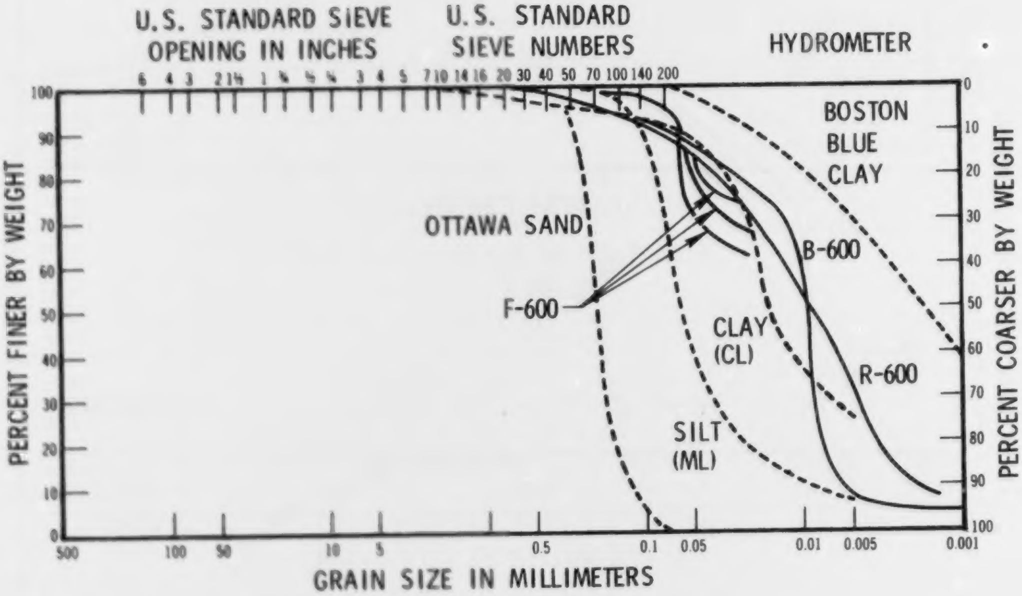


a. SLUDGE 100 (Eastern Coal, Lime Absorbent)



b. SLUDGE 400 (Eastern Coal, Limestone Absorbent)

Figure 25. Grain size distribution: (a) untreated and (b) treated wastes.



SLUDGE 600 (Western Coal, Limestone Absorbent)

Figure 26. Grain size distribution: Processes B and F results.

In general, treatment of the sludges tended to reduce specific gravity although a few values were slightly higher after treatment. Changes were not reported as process-dependent. The specific gravities are reported in Table 28. Values were in the range of common minerals and soils such as kaolinite, dolomite, and bauxite.

Bulk density, i.e., air-dry unit weight, did not exhibit as wide a range of values after treatment as before treatment. The range of values for all treated sludges was reported as 65.7 lb/ft^3 to 105.9 lb/ft^3, while for untreated sludges values ranged from 47.4 lb/ft^3 to 157.2 lb/ft^3. There were some large reductions, as well as some increases, in bulk density resulting from treatment, but none appeared to be dependent upon the type of treatment process.

Dry density, i.e., oven-dry unit weight (samples dried at 60° C), was generally lower after treatment by Process B and considerably higher after fixation by Process E. The dry densities of sludges fixed by Process E are in the range of lightweight clays and silts.

A large increase in water content resulted from treatment of sludges by Process B. Water contents for B-treated sludges ranged from 2 to 37 times those of the untreated sludges. Sludges treated by Process E remained at low water contents, in the range of the untreated sludges. All water contents are shown in Table 29.

Porosity and void ratio remained about the same after treatment by Process B. Process E resulted in lower values of porosity and void ratio. Comparisons of sludges, untreated as well as fixed, with soils in terms of void ratio and porosity were compared and are presented in Figure 27.

5.1.3.1.1.3 Engineering Properties

The results of three standard engineering properties tests were reported on selected fixed sludges. A 15-blow compaction test was conducted on 9 samples of sludges fixed by Process B to determine the density-moisture relationships of the fixed sludges. The compressive strengths of specimens of sludges treated by Processes E and F were determined by performing unconfined compression tests. Durability of sludges fixed by Process E was determined by the wet-dry brush test.

Results of the compaction test were reported and are summarized in Table 33. The results show that sludges fixed with Process B exhibit low dry densities and high optimum moisture contents when compared to basic soil types. A comparison of the dry densities of sludges fixed with Process B before and after the application of the compactive effort of the 15-blow compaction revealed that in two cases, B-400 and B-1000, a more dense material resulted. Furthermore, samples B-100 and B-600 were unaffected by the test, and another sample, B-500, had higher densities before the compaction.

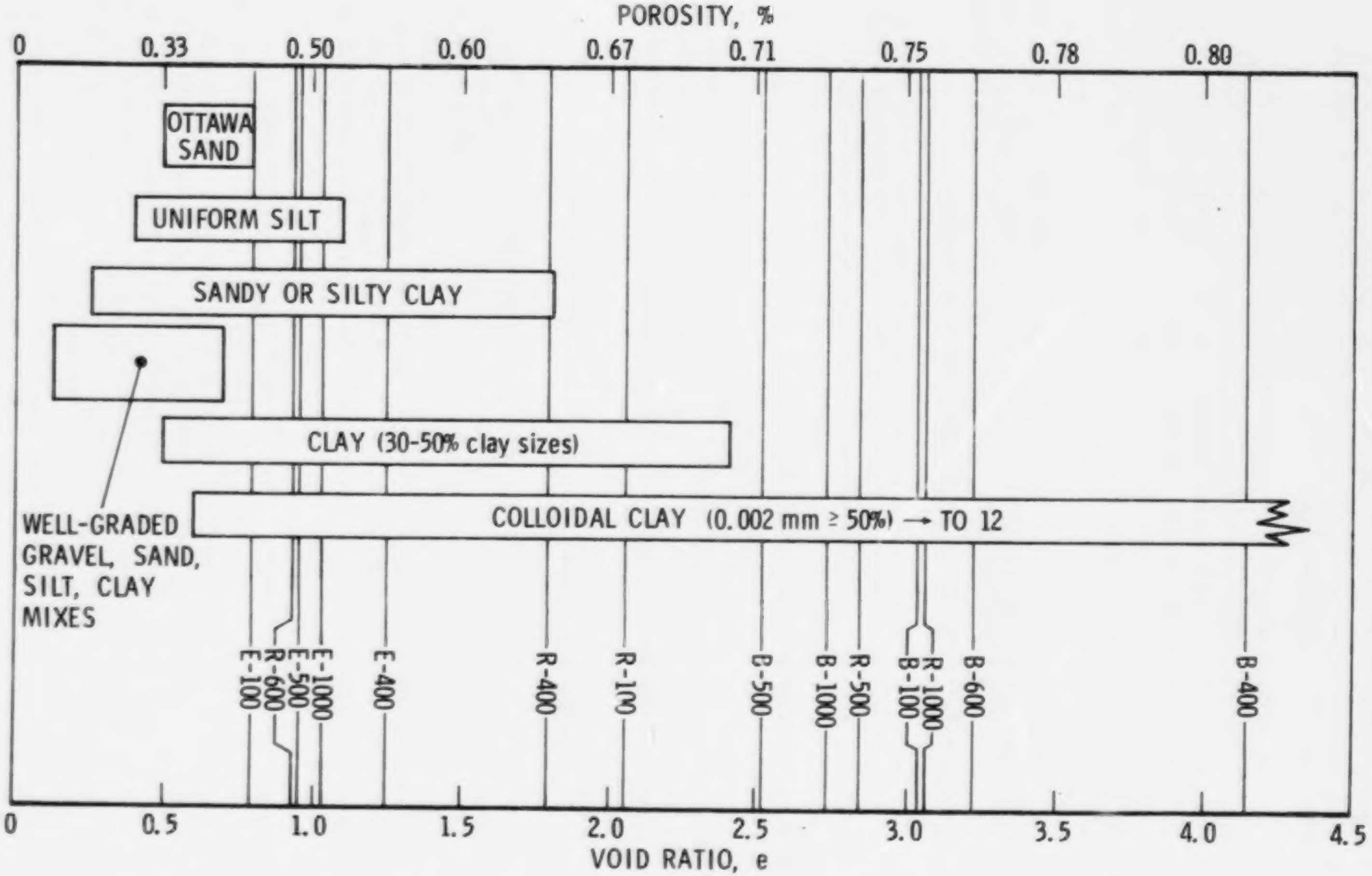


Figure 27. Porosity and void ratio of soils compared with untreated and treated wastes.

The unconfined compressive strengths of samples of sludges fixed by Processes C, E, and F after curing are also reported (Table 29). Additionally, the modulus of elasticity was determined from the stress-strain curve for each of the treated sludges. Sludges fixed by Process E lost their soil consistency and became quite hard, apparently undergong a cementation process. Compressive strengths of sludges fixed by Process E were comparable to those of low strength concrete (3000 psi at 28 days). The stress-strain measurements also showed that sludges fixed by Process E were brittle, failure occurring at low strains. However, sludges fixed by Process F failed at very high strains, indicating an elastic consistency, though compressive strengths were lower than the sludges fixed by Process E.

A wet-dry brush test was performed as a measure of durability on samples fixed by Process E. These sludges performed fairly well, generally surviving the 12 cycles, at which time the test was terminated in accordance with the ASTM test procedure. The weight loss reported for samples fixed by Process E was in the range of 7 to 16 percent.

5.1.3.1.2 Chemical Properties

The leaching tests are aimed at measuring the rate of pollutant migration into an aqueous medium. One hundred sixty-two columns have been assembled to simulate the dispersed flow and leaching of pollutants at surfaces or cracks within the treated waste matrix.

For treated wastes, a leaching surface-to-sludge volume ratio of approximately 1.0 to 1.5 is being tested. A treated sludge core, 3 inches in diameter and with a volume of approximately 0.25 ft^3, has been placed within a 4-inch (inner diameter) transparent-plastic column, and the annular space has been filled with polypropylene pellets. The leachate flow rate is controlled to maintain a fluid velocity in the range of 10^{-5} to 10^{-6}cm/sec. This rate has generally been achieved for all samples of treated wastes, on the basis of flow patterns established for these leaching columns. The control of flow rate through the untreated wastes is a function of the waste permeability itself and is not subject to control methods.

Two leaching fluids were used to represent both sides of the pH spectrum and to provide some insight into the effect of leaching pH, one fluid being water saturated with carbon dioxide having a pH of 4.5 to 5.0 and the other being deionized water buffered with boric acid with a pH of 7.5 to 8.0. The columns are triplicated for each leaching solution. Analysis of data has indicated no significant differences in leachate pollutant concentration from either of the two leaching solutions. Therefore, based on results achieved through mid-1976, use of the slightly alkaline leaching solutions has been discontinued; that with the nominal pH of 4.7 will continue to be used in the study. A modification in the numbers of leachate analysis from the columns has been implemented. Triplicate columns will still be maintained and sampled quarterly, but only one sample will be analyzed (Table 34). The remaining two samples will be retained in the event results warrant additional analyses.

TABLE 34. CHEMICAL CHARACTERISTICS TESTS OF UNTREATED AND TREATED FGC WASTES

<table>
<tr><th colspan="3">Chemical Analysis: Concentration as a Function of Time</th></tr>
<tr><th>Cations</th><th>Anions</th><th>Organic</th></tr>
<tr><td>Arsenic</td><td>Chloride</td><td>Chemical oxygen demand</td></tr>
<tr><td>Beryllium</td><td>Cyanide</td><td>Total organic carbon</td></tr>
<tr><td>Cadmium</td><td>Fluoride</td><td></td></tr>
<tr><td>Calcium</td><td>Nitrite</td><td></td></tr>
<tr><td>Chromium</td><td>Nitrate</td><td></td></tr>
<tr><td>Cobalt</td><td></td><td></td></tr>
<tr><td>Copper</td><td>Sulfate</td><td></td></tr>
<tr><td>Lead</td><td>Sulfite</td><td></td></tr>
<tr><td>Magnesium</td><td></td><td></td></tr>
<tr><td>Manganese</td><td></td><td></td></tr>
<tr><td>Mercury</td><td></td><td></td></tr>
<tr><td>Molybdenum</td><td></td><td></td></tr>
<tr><td>Nickel</td><td></td><td></td></tr>
<tr><td>Selenium</td><td></td><td></td></tr>
<tr><td>Sodium</td><td></td><td></td></tr>
<tr><td>Zinc</td><td></td><td></td></tr>
<tr><td colspan="3">Leachate pH</td></tr>
<tr><td colspan="3">Leachate Electrical Conductivity, μmhos/cm</td></tr>
</table>

A new task has been incorporated into the program. It is to determine the leaching effects of placing untreated and treated FGC sludges in a sanitary landfill environment and to determine the leachability under such environmental conditions. The experiments will be carried out by the use of lysimeters, and investigative efforts are being designed to minimize the scale effect of the small laboratory lysimeters to maintain comparability of results with field conditions. Additional information is provided in Section 5.1.3.1.3.

5.1.3.1.2.1 Untreated Wastes

Characteristics of the untreated wastes were reported in Reference 15 and are outlined in this section.

The results of the digests of the FGD sludges for metals are summarized in Table 35. The major metal species appear to be a reflection of the type of absorbent employed in the scrubber. The heavy metals that are present to a consistent degree in the sludges include chrome, nickel, and lead. In the case of the limestone and double alkali scrubbers, a possible correlation may be made with respect to coal source. For the limestone scrubber, the Western coal sludge is consistently higher for all metals included in the analysis; for the double alkali scrubbers, the reverse situation is true.

Conductivity measurements of the column leachates, which are indicative of the TDS, are shown in Figure 28. For most of the FGD sludges studied, there is an initial high concentration followed by a subsequent decline.

The leaching of lead was reported as an example of the type of results being obtained. These are summarized in Table 36. The trends observed are similar to the conductivity (TDS) data, i.e., a high concentration followed by a drop and leveling off. Data similar to that for lead may be used in assessing the environmental impact associated with the leaching of metals from FGD wastes.

5.1.3.1.2.2 Treated Wastes

Typical treated waste leachate analyses for sulfate and TDS were published in References 4 and 15 and presented in the last report summary (Ref. 1) (Figures 29 and 30). Figures 31 through 33 from Reference 4 are repeated here for the convenience of the reader. The results and data acquired subsequently are being analyzed and will be presented in the next report. Pertinent data relative to pH characteristics are discussed in the following paragraphs.

The pH for untreated and fixed sludge specimens are presented in Figure 34. These data are reported as the mean values for all leachate replicates over the sampling period, from the pH 4.7 buffered leach solution, and represent a spatial representation of pH for comparative purposes between samples.

TABLE 35. RESULTS OF SLUDGE DIGESTS, METALS

Parameter	Sludge Number				
	100	400	600	500	1000
	Concentration, ppm, dry weight basis				
Be	10.4	3.9	23.7	2.4	0.01
Ca	63,500	158,700	196,250	69,100	59,200
Cd	2.8	12.9	17.7	22.6	3.1
Cr	98.2	90.6	131.9	54.1	24.5
Cu	87.3	169.7	239.8	90.9	38.5
Mn	159.2	251.8	595.7	169.7	40.3
Mg	5,630	18,700	33,900	9,740	5,430
Ni	137.4	215.3	202.4	123.5	75.4
Pb	54.1	155.3	287.8	131.6	64.9
Zn	166.1	330.8	333.7	228.6	67.2
Co	35.8	4.4	46.7	2.7	0.05
Mo	23.6	147.1	140.5	98.4	4.8
Na	17,100	40,200	99,500	28,200	18,700

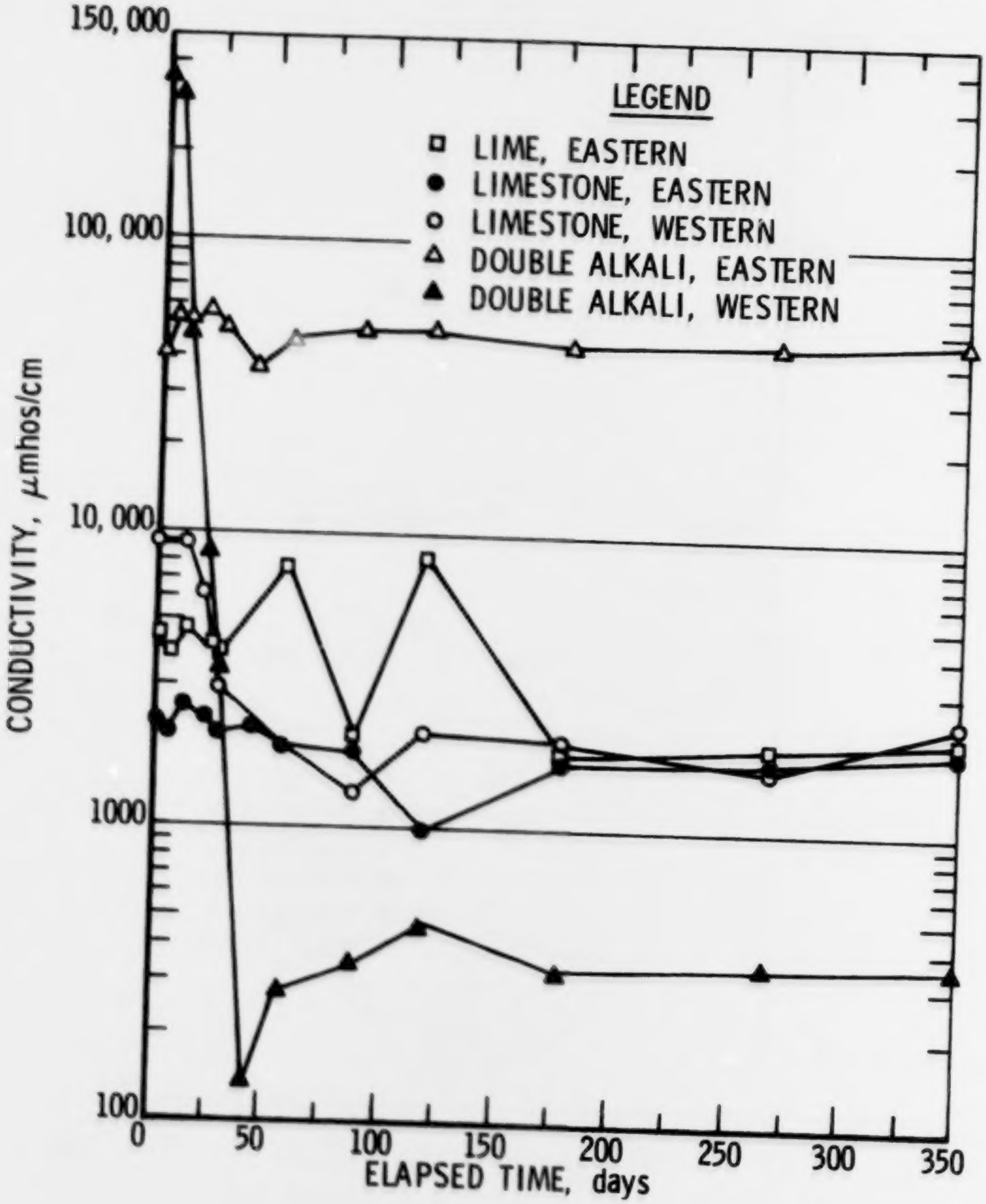


Figure 28. Leachate conductivity, untreated FGD sludges.

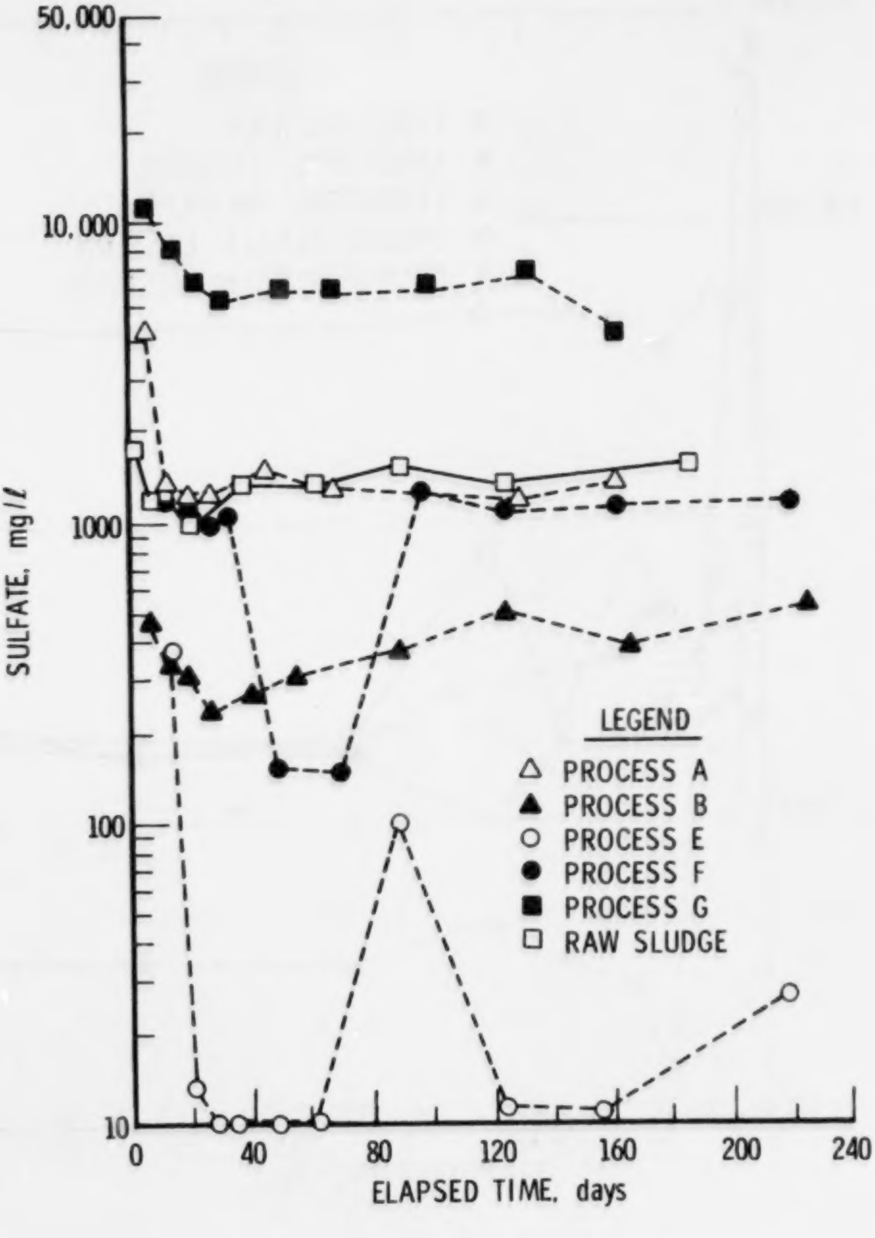


Figure 29. Leaching results: sulfate, sludge No. 100.

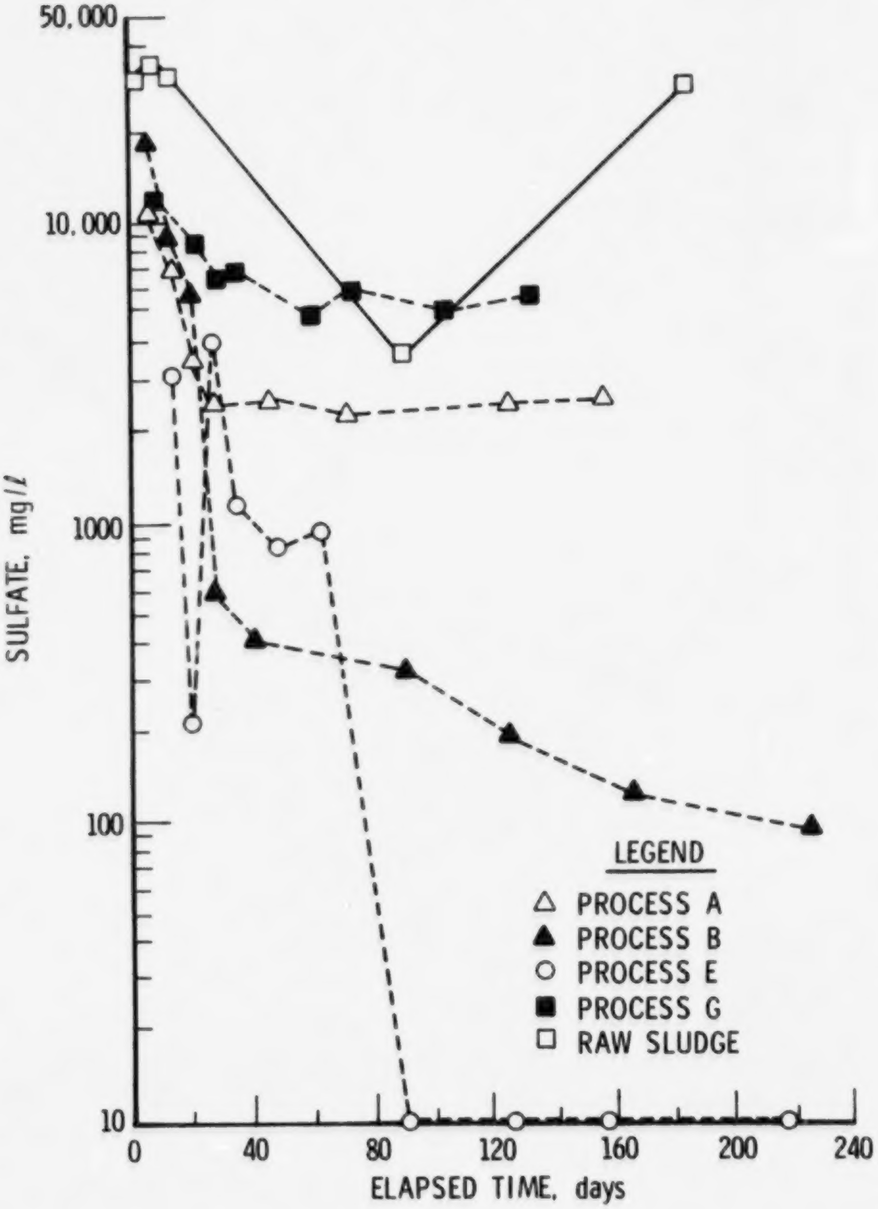


Figure 30. Leaching results: sulfate, sludge No. 500.

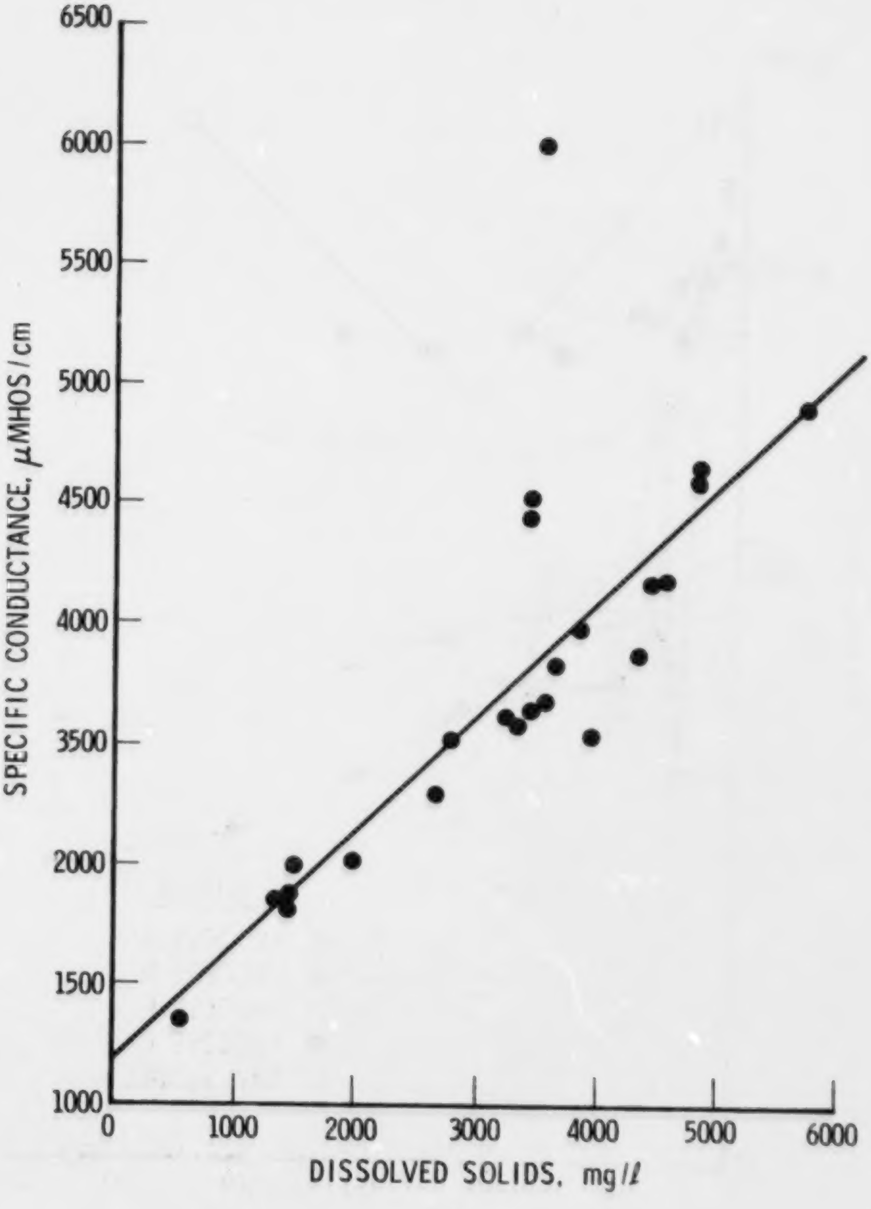


Figure 31. Conductivity versus dissolved solids.

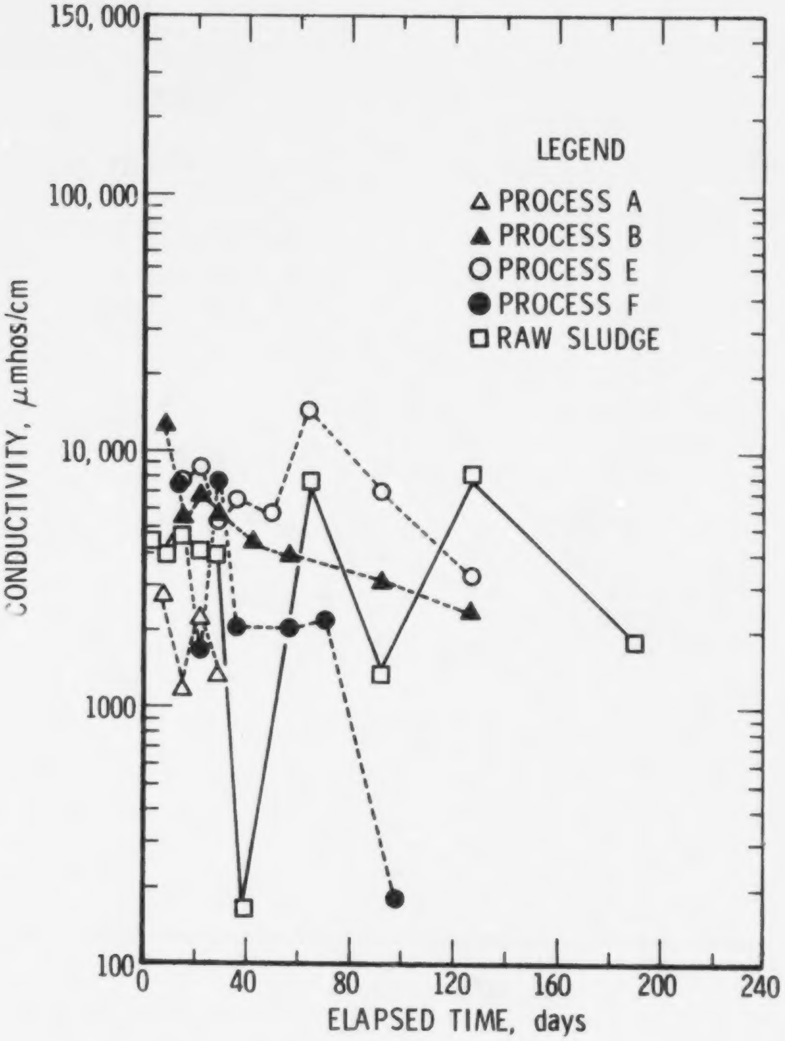


Figure 32. Conductivity of leachate, sludge No. 100.

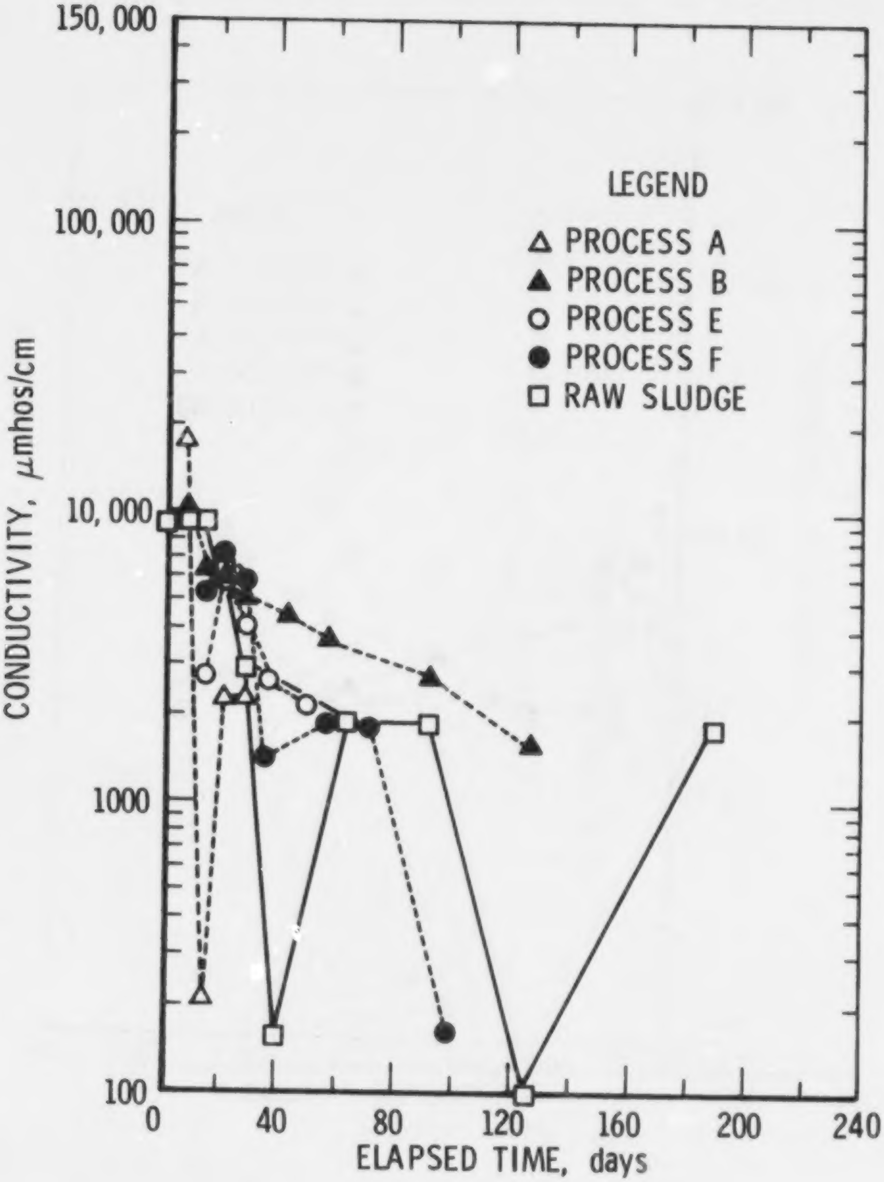


Figure 33. Conductivity of leachate, sludge No. 600.

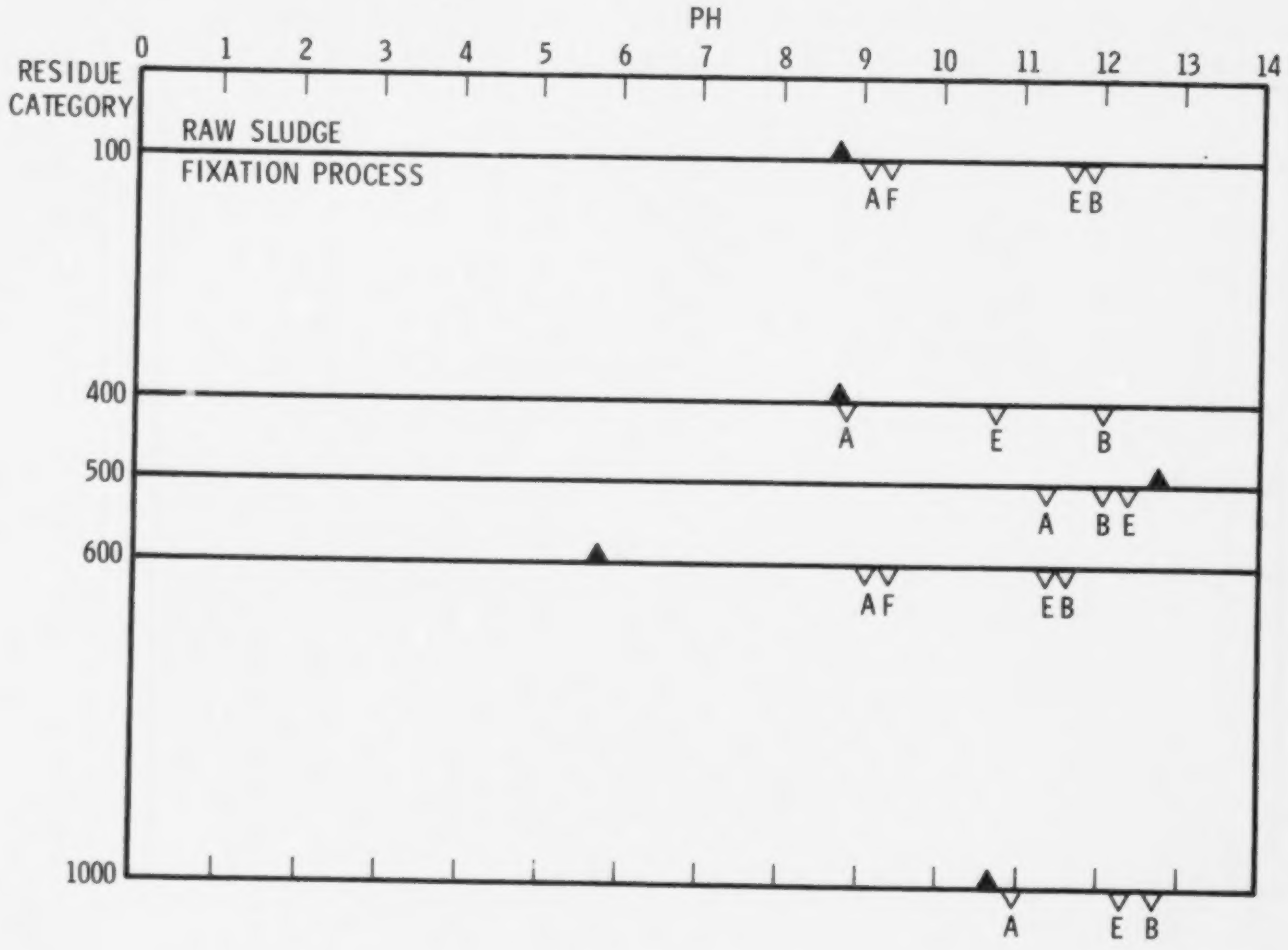


Figure 34. Leachate pH for untreated and treated residues.

TABLE 36. LEACHATE DATA, LEAD

Elapsed Time, days	Sludge Number				
	100	400	500	600	1000
	Concentration, $\mu g/\ell$ [a]				
1	98	17	22	71	870
7	6	15	1000	22	780
14	6	3	500	26	360
21	1	1	330	--	490
28	1	1	220	1	7
42	1	1	240	1	5

[a] Lead background level is 4 $\mu g/\ell$.

It was suggested in Reference 4 that pH may have a predominant effect on leaching characteristics and be related to observed pollutant mobility, particularly for the metals which are less mobile at a high pH due to formation of insoluble hydroxides.

5.1.3.1.3 Environmental Effects

An evaluation of the potential effects of placing untreated and treated FGD wastes in a landfill environment is the objective of this recently defined 52-month task. Experiments will be conducted, using lysimeters. The test conditions are being designed to minimize the scaling factor effect of the lysimeter data as it relates to field conditions.

Untreated and treated FGC sludges will be placed in cells which are 3 ft in diameter and 6 ft deep. The cells will be constructed or lined with nonreactive material capable of withstanding stresses due to temperature changes, loading conditions, and any other physical loads as may result from movement. The cells will be located in a controlled environment. Their number and distribution are identified in Table 37.

Distilled water will be applied weekly, at the rate of 24 inches per year, to the top layer of material. Temperature and redox potential will be monitored by temperature sensors and platinum electrodes in the soil

TABLE 37. FGC SLUDGE TEST CELL MATRIX

Sludge	Type 1	Type 2	Type 3
Untreated	11[a]	12	13
Treated, Processor 1	14	15	16
Treated, Processor 2	17	18	19

[a] Refers to test cell identification number.

layers. Three inches of nonreactive silica gravel will be placed in the bottom of each lysimeter. Soil will be placed on top of the gravel to a depth of one foot in all lysimeters and compacted so that no direct channeling occurs. The cells are being designed such that leachate samples can be obtained below the soil layer and at the soil-sludge interface. The intent is to determine any improvement in the quality of the leachate after passing through the soil.

Sources of the soil and FGD wastes are being selected to more nearly simulate in-situ disposal conditions. The soil used in the lysimeters will be chemically and physically characterized initially and after termination of the 3-year leaching experiment. The soil parameters that will be measured are pH, texture, total iron (Fe), free iron oxides (Fe_xO_y), total aluminum (Al), free and/or exchangeable aluminum oxides (Al_xO_y), exchangeable Fe, total manganese (Mn), manganese oxides (Mn_xO_y), exchangeable Mn, water soluble Mn, and the major type of clay mineral present in the clay fraction. A distilled water and dilute hydrochloric acid leach of the soil will be conducted and the resulting solutions analyzed for Cr, Hg, Ni, Pb, Cu, As, Be, Cd, Se, V, and Zn. It is expected that by combining the data from the two leaching systems with the data on the chemical parameters listed, information on the effect of leachate on soil under a disposal site can be obtained.

Leachate will be sampled, and the pH, electrical conductivity, and temperature will be determined. The leachate will then be analyzed for the constituents shown in Table 38. The sampling frequency and analytical schedule is being determined cooperatively by the WES Principal Investigator and the EPA Project Officer.

TABLE 38. LEACHATE ANALYSIS

Aluminum
Arsenic
Beryllium
Boron
Cadmium
Chromium
Copper
Calcium
Iron
Mercury
Magnesium
Manganese
Sodium
Phosphorous
Potassium
Nickel
Lead
Selenium
Vanadium
Zinc
Sulfate
Chloride
Sulfite
Nitrite
Nitrate
Ammonium
Cyanide
Total organic carbon (TOC)
Total dissolved solids (TDS)
Chemical oxygen demand (COD)

5.1.3.2 Site Survey and Environmental Assessment of Existing Solid Waste Disposal Sites

The site investigation task is divided into preliminary investigative, sampling, analysis, and environmental assessment. It is expected that candidate site characteristics related to history, waste characteristics, geology, and hydrology will be defined and quantified. A total of three FGD disposal sites have been selected. A boring and sampling program is also being defined. Samples of the waste, soil, bore water, and groundwater will be taken and analyzed for chemical constituents and partition of pollutants (Table 39).

The principal goal of this task is to investigate contaminant migration from disposal sites and relate findings to site history and disposal operations. Background samples from outside the disposal site will be obtained for baseline data and comparative purposes.

The basic objectives for this task have been defined as follows:

a. Qualify and quantify general site characteristics related to history, residue characteristics, geology, and hydrology

b. Develop and execute a sampling schedule based on the results of (a) for residue, soil, and groundwater

c. Analyze the samples for physical and chemical properties including the partitioning of pollutants

d. Obtain an assessment of land disposal as a function of waste category, disposal operations, and environmental factors

The first R&D report (Ref. 1) indicated that a number of contacts had been made with companies known to have operational FGD sludge disposal sites, and one site has been visited and rejected for study because of geologic conditions. Since that time, two sites in the Midwest have been tentatively selected, with a third one being confirmed. Borings have been completed at the latter site, and others are expected to be taken as soon as approval for study of the other sites is received.

5.1.3.3 Evaluation of Existing FGC Waste Fixation Technology

During this portion of the study, a compilation of FGC waste treatment processes currently available will be made and their respective areas of application identified. The development of a methodology for selection and application of fixation technology based on economic analyses and process evaluation is also planned. The latter task includes the definition and development of a screening test for rapid and accurate assessment of the potential environmental impact associated with the fixation and disposal

TABLE 39. CHEMICAL ANALYSES ON SAMPLES FOR SITE SURVEYS

Arsenic	Selenium
Beryllium	Zinc
Cadmium	Sulfite
Chromium	Sulfate
Cyanide	Boron
Copper	Chloride
Mercury	Vanadium
Magnesium	Nitrite
Manganese	Nitrate
Nickel	Hydrocarbons
Iron	Total organic carbon
Lead	

of FGC wastes. The program is currently under way and is expected to extend over a two-year period. Specific program objectives include:

a. Development of a rational method for selection and application of fixation technology based on economic analysis and process evaluation

b. Development of a screening test for fast and accurate environmental analysis of fixation methodology (to include physical and leach testing)

c. Compilation of a list of fixation processes currently available and their respective areas of application

The same FGC wastes that were evaluated in the pollution potential task (Table 27) will be treated with a number of materials selected on the basis of a survey of identified second generation FGC waste treatment processes and of the Corps of Engineers soil and dust control materials and methods.

The list of candidate materials identified in Reference 1 has been expanded, and the materials listed have been tested (Table 40). Limited testing, appropriate to define optimum concentration of additives, will be performed. The screening criteria which are being defined will be developed to evaluate the efficacy of potential fixation processes and also the environmental effects of solid waste on a disposal site.

Each potential chemical fixative is being screened in the following manner: Specimens of each FGD sludge type are mixed with fixative at rates of 0, 5, 10, and 15 percent of the dry sludge weight and allowed to air dry. Following the mixing, but prior to air drying, a portion from each mix is oven-dried. Water is added to the oven-dried samples until each specimen lies under approximately one inch of water. The portions of the samples left to air dry thus far have usually assumed a solid or semisolid (form) condition. However, the samples that were oven-dried and then immersed in water usually became soft to fluid.

Four samples of each chemical will also mixed with each of the five sludge types at the rate of 15 percent of the dry sludge weight. The testing methodology to be applied to these samples is currently being defined.

Contact was made with approximately 25 chemical treatment organizations (manufacturers and processors) to elicit their participation in the program to evaluate second generation processes. Those indicating interest in participating are listed in Table 41. Final determination as to the extent of participation of each processor has not been defined.

5.1.4 Characterization of Effluents from Coal-Fired Power Plants (TVA)

This interagency-funded program with TVA is being conducted by the Power Research Staff, Chattanooga, Tennessee. Studies of liquid- and solid-related effluents are under the cognizance of Julian W. Jones, the EPA Industrial Environmental Research Laboratory (IERL), Research Triangle Park, North Carolina; studies of gaseous effluents are under Ron A. Venezia, also of IERL. This report addresses the work in the liquid-and solid-waste areas only.

The water- and solid-waste program is comprised of 5 tasks extending over a period of approximately 38 months. A final report is planned for late 1978. Chemical properties of coal pile drainage will be characterized and quantified. A second task will be an assessment of the adjustment of pH on the physical and chemical composition of ash pond effluents for purposes of meeting effluent standards. The frequency of sampling and analysis for an effective ash pond monitoring program will be defined, and a monitoring system designed and tested. An assessment of the total residual chlorine, its components (free and combined), and chlorinated organics discharged from a once-through cooling system will be conducted; lastly, the effects of coal ash leachate on groundwater quality will be characterized and quantified. The status of the various tasks as of November 15, 1976 are summarized in

TABLE 40. TREATMENT MATERIALS BEING TESTED

Calcium carbide
Lime
Cement
Arquard 2HT
TACSS 025 (also a 20% sample)
Asphalt emulsion (67.8% asphalt)
AM 9
Fly ash
TACSS T020 NF (also a 20% sample)
Arothane 170
Aropol 7110
Chrome lignin
Sodium silicate
Aniline furfural
TACSS C400
TACSS C7[a]
TACSS ST[a]

[a] To be tested.

TABLE 41. SECOND GENERATION TREATMENT PROCESSES

I. U. Conversion Systems, Inc.
Research Center
P.O. Box 331
Plymouth Meeting, PA 19462
215/825-1555
Contact: Dr. Steve Taub

Wehren Engineering Corp.
East Main Street Extended
Middletown, NY 10940
914/342-5881
Contact: Mr. Dennis Fenn

Protective Packaging, Inc. (NECO)
328 Production Court
Jeffersontown, KY 40299
502/491-8300
Contact: Mr. Bruce Goreham

DRAVO Corporation
Product Research
Neville Island
Pittsburgh, PA 15225
412/771-1200
Contact: Mr. Laszlo Pasztor

CHEMFIX, Inc.
505 McNeilly Road
Pittsburgh, PA 15226
412/343-8611
Contact: Mr. Ronald Polosky

Air Frame Mfg. & Supply Co.,
(TACSS)
7407 Fulton Avenue
North Hollywood, CA 91605
213/875-2094
Contact: Mr. Robert F. Jenson

Werner & Pfleiderer Corp.
160 Hopper Avenue
Waldwich, NJ 07463
201/652-8600
Contact: Mr. John E. Steward

Aerojet Energy Conversion Co.
P. O. Box 13222
Sacramento, CA 95813
816/355-2255
Contact: Mr. Roy E. Jones

Chem Nuclear Systems, Inc.,
P.O. Box 1866
Bellevue, WA 98009
206/747-5331
Contact: Mr. C. D. Johnson

Environmental Technology Corp.
289 Casa Drive
Pittsburgh, PA 15241
412/431-8586
Contact: Mr. Albert R. Kupiec

ANEFCO Company
151 East Post Road
White Plains, NY 10601
914/946-4631
Contact: Mr. John Murphy

United Nuclear Industries
Commercial Division
1201 Jadwin Avenue
Richland, WA 99352
509/946-7661
Contact: Mr. Harold W. Heacock

Sludge Fixation Technology
Orchard Park, NY

the following paragraphs. A tabulation of the sites being studied as part of the various tasks are shown in Table 42.

5.1.4.1 Characterization of Coal Pile Drainage

The Kingston and Colbert steam plants were selected as sites for the coal pile drainage characterization studies. Composite samples were taken at Kingston of the surface runoff pumped to the ash pond. Pumped volume is being correlated with rainfall.

Sampling has been delayed at Colbert because of equipment failures. As a result of information obtained during the Kingston study, it has prompted a change in sampling strategy. Samples at Kingston were weekly composites and were reported to vary with the rainfall regime. Samples to be taken at Colbert will be composite samples of individual storms and are expected to define more clearly the effect of rainfall intensity and duration in establishing the character of coal pile drainage.

Elution tests of the coal and analysis of elutriate are being conducted. In addition to determining the chemical species in the liquid phase, coal pH, neutralization potential, and potential acidity tests will be performed on each coal sample. The pH of the coal is being determined, and modifications of techniques used for coal mine overburden analyses are being considered.

Abundant information on the acid potential of coal mine overburden is reported to be available but very little on coal. If the data from the tests on potential acidity of coal correlate favorably with overburden data, it may reduce the number of coal samples that will be analyzed. SOXHLET extraction is being used for obtaining analysis of the acid potential.

Sampling is nearly complete at Kingston, with the collection of 19 weekly composite surface runoff samples. Results of the analyses from the samples are reported in Table 43 and summarized in Figure 35. Concentrations of Cr, Pb, Hg, Ba, Cd, Ti, Be, and Sb were consistently low or below detection limits and were not reported. Matrix interferences prevented the determination of chlorides. Sampling at the Colbert steam plant was initiated in November.

Mass flows of several constituents were reported for the month of June 1976. The total flow for this month was 3.19 million gallons with a requirement of 9.7×10^5 equivalents of base for neutralization to pH 7. During this period, 12 tons (1.1×10^4 kg) of iron, 4 tons (3.6×10^3 kg) of aluminum, 800 lb (360 kg) of manganese, 80 lb (36 kg) of nickel, and 30 lb (14 kg) of copper, along with large quantities of sulfate, suspended solids, and hardness were leached from the coal pile.

An analysis was performed of a rainfall sample collected during a storm that occurred on June 29 and 30. The storm had a duration of 33 hours, with a total precipitation of 1.35 in (3.43 cm). Total precipitation

TABLE 42. LOCATION AND STATUS OF FIELD SITE STUDIES

Task	Paragraph Discussed	Remarks
Characterization of Coal Pile Drainage	5.1.4.1	Sampling and analysis is under way at Kingston. Problems associated with the sampling equipment have delayed sampling at Colbert. Resolution is expected shortly.
Effects of pH Adjustment on Ash Pond Effluent	5.1.4.2	Colbert, Kingston, and Paradise.
Design of Monitoring Program for Ash Pond Effluents	5.1.4.3	Colbert and Kingston. (Another site may be selected.)
Chlorinated Once-Through Condenser Cooling Water Discharge Study	5.1.4.4	The Kingston plant was originally selected for study. However, preliminary studies indicated that the intake water pH was high and varied seasonally. Because of these widely varying conditions, further testing was dropped, and the John Sevier plant was selected as the site for future work.
Effect of Coal-Ash Leachates on Ground Water Quality	5.1.4.5	The Kingston and Colbert generating plants were selected as the site for this investigation. Soil core samples were taken and monitoring wells were installed at Kingston. A one-year sampling program is planned. Because of geological complications at Colbert, the Widow's Creek plant was selected as a replacement. Field work, soil sampling, and monitoring of the well installation were completed recently.

TABLE 43. ANALYSIS OF COAL PILE DRAINAGE

Week No.	pH	Acid 7.0 pH mg/l as $CaCO_3$	Conductivity µmhos/cm	SO_4	Dissolved Solids	Suspended Solids	Fe	Mn	Cu	Zn	Al	Ni	Ca	Mg	As	Se
				mg/ℓ												
1	2.9	1700	2400	2600	3200	550	510	27.0	0.56	3.7	190	1.70	240	1.2	0.010	0.030
2	2.6	1100	2400	1800	2500	110	300	8.9	0.43	2.3	66	0.74	190	64	0.010	<0.002
3	2.8	5300					1800	33.0	1.30	6.3	350	3.50	400	320	<0.045	<0.002
4	2.5		5200	4500	9400	150	1100	31.0	0.84	5.4	300	2.30	31	270	0.150	<0.002
5	3.0	2200	4600	3100	6800	140	790	31.0	0.73	5.1	270	2.20	220	220	0.110	0.006
6	2.9	2400		6600	7500	120	840	31.0	0.89	5.1	240	2.40	340	260	0.070	0.008
7	3.0	1400		2700	3100	8	240	11.0	0.62	2.6	78	1.20	230	7.6	0.040	0.006
8	3.0	300	4000	4500	5900	2300	580	23.0	1.10	6.6	240	2.50	320	160	0.360	0.005
9	2.9	3700	4200	4600	7400	1400	620	34.0	1.10	5.6	310	2.70	320	210	0.310	0.011
10	2.8	5500	5300	7200	11000	210	760	39.0	1.40	9.2	370	3.90	330	340	—	0.008
11	2.3	6100	5600	7400	13000	440	1700	32.0	1.10	16.0	350	3.90	370	350	0.600	0.008
12	3.0	1700	9500	1800	3500	280	470	14.0	0.59	10.0	96	1.40	260	95	0.080	
13	2.9	5900	5400	7800	12000	46	1800	33.0	1.10	8.1	440	4.00	280	380	0.180	0.003
14	3.0	3900	4400	9500	6300	480	1000	31.0	0.71	5.3	260	2.30	300	320	0.260	0.001
15	3.1	7100	5900	7600	16000	61	1400	41.0	0.63	13.0	380	4.30	490	480	0.005	0.002
16	2.6	5900	5500	9600	14000	170	1600	45.0	1.40	9.9	250	4.50	430	440	0.200	0.001
17	2.5	3600	3700	3700	7600	75	790	28.0	0.60	4.6	430	2.20	300	17	0.084	0.004
18	3.0	340	4700	4000	8400	1900	750	27.0	0.58	4.1	220	1.80	350	27	0.310	0.001
19	2.3	3100	4400	3800	4700	39	780	26.0	0.70	4.0	180	1.60	320	150	0.180	0.001

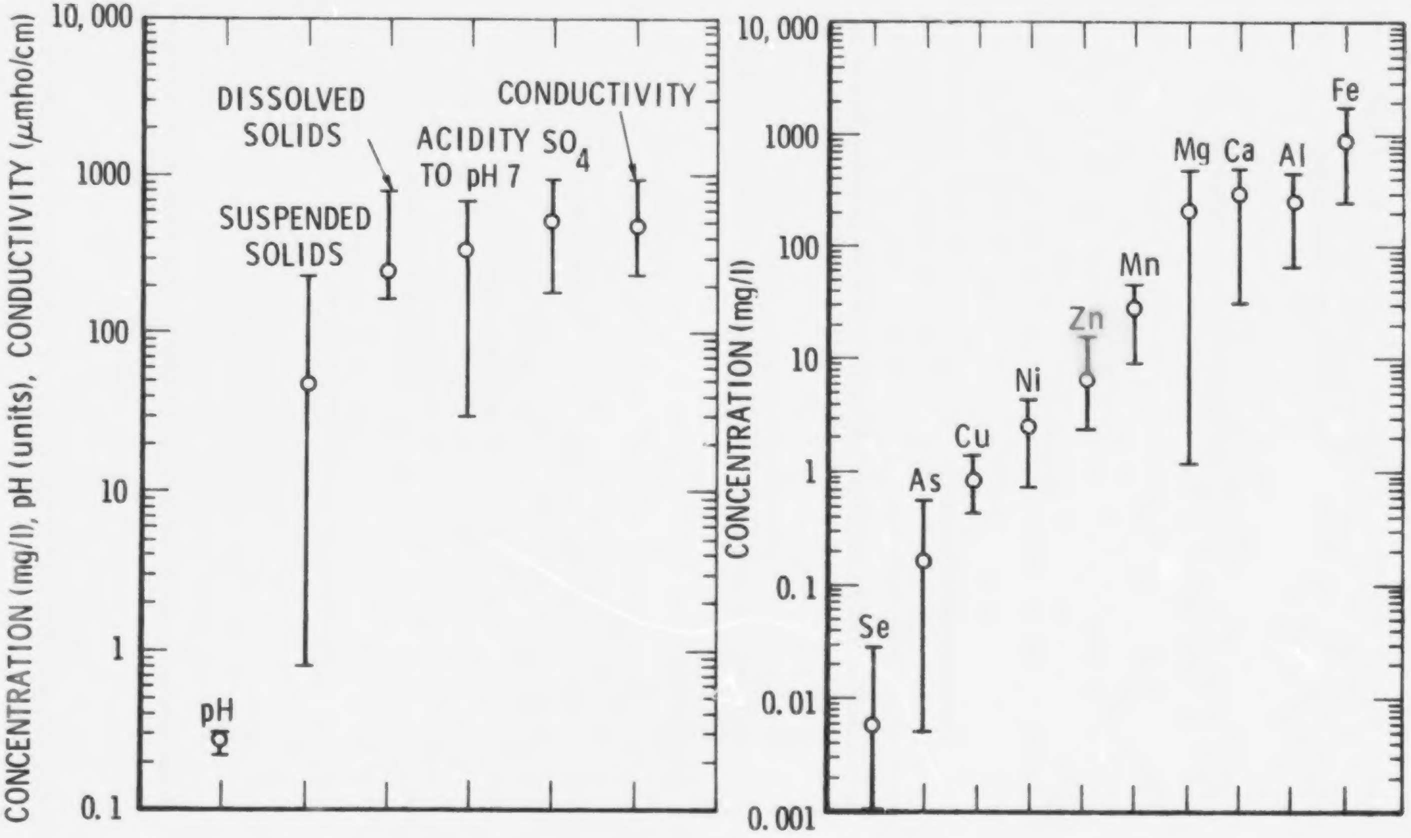


Figure 35. Means and ranges of coal pile drainage analyses.

for June was 4.74 in (12.04 cm). Concentrations of several constituents were analyzed in the rainfall sample, and loadings were extrapolated for the month of June. Calculated values were 8.0 lb (3.6 kg) of iron, 11.5 lb (5.2 kg) of aluminum, 0.6 lb (0.27 kg) of manganese, 2.9 lb (13. kg) of nickel, 4.0 lb (1.8 kg) of copper. Thus, contaminants in rainfall were considered to be insignificant except for copper, which appeared to contribute 13 percent of the copper in the runoff. Another sample was collected for analysis during October 1976.

5.1.4.2 Effects of pH Adjustment and Suspended Solids Reduction on Trace Metals and Power Plant Ash Pond Effluent

In this study, an assessment and quantification is being made of the chemical and physical composition of ash pond effluent after the pH of the ash pond is adjusted. Mathematical modeling and laboratory settling tests are being made in addition to physical and chemical characterization of ash pond suspended solids from the Colbert, Kingston, and Paradise plants.

A mathematical model and computer iteration method has been developed that simulates the batch settling characteristics of fly ash and bottom ash in a continuous ash pond system. The model permits use of batch settling mechanisms to compute the necessary retention time in an ash pond for a predefined suspended solids removal efficiency.

A summary of the tests and analyses being conducted is provided in Table 44. The ash settling characteristics will be evaluated in relation to the original percentage of ash content in the sluice water, specific gravity of ash, and particle size of ash.

Kinetic studies were performed to investigate the rate of pH change and dissolved solids released when fly ash was contacted with Tennessee River water. It was reported that for fly ash having neutral and alkaline fly ash sluice waters containing 0.5 to 3 percent suspended solids concentrations, the equilibrium curves of pH leveled off within three hours after ash and river water contact. The equilibrium concentrations of conductivity leveled off within four hours. For fly ash resulting in acid ash sluice water and containing 0.5 to 3 percent suspended solids concentrations, both the equilibrium curves of pH and conductivity leveled off within 30 minutes after ash and water contact.

The dissolved and suspended nature of trace metals in ash pond discharges was investigated. Grab samples from Colbert and Kingston steam plant ash pond discharges, as well as samples from all other TVA fossil-fired plants, were analyzed for several trace metals. Based on preliminary data, some general conclusions were reported for cadmium, chronmium, copper, iron, lead, manganese, and zinc. Their removal may be facilitated by adjusting the pH to 8 or 9 and by increasing removal of suspended solids. Arsenic and selenium were found to be exceptions.

TABLE 44. SUMMARY OF LABORATORY TESTS AND ANALYSES

Power Plant	Sluice Water pH			Sluice Water Settling Tests				Chemical Analysis		
	Intake	Entrance to Ash Pond	Ash Pond Water Adjusted to	ESP Ash	Mechanically Separated Ash	Fly Ash	Bottom Ash	Ceno-Spheres[a]	Fly Ash Sluice Water[b]	Ash Pond Discharge Water[b]
Colbert	7.7 - 8.6	8.0 - 12.5	6.0 and 9.0	1, 2, 3% suspended solids	1, 2, 3% suspended solids	1, 2, 3% suspended solids	1, 2% suspended solids	Yes	0.03 ash-to-water ratio	Yes
Kingston	Neutral		9.0	1, 2%	1, 2%	1, 2, 3%		Yes	0.03	Yes
Paradise	Acid		6.0 and 9.0			1, 2, 3%		Yes	0.03	Yes

[a] Analyze for total Al, Ca, Fe, K, Mg, Na, Si, Ti, As, Cd, Cr, Cu, Pb, Hg, Ni, Se, and Zn.
[b] Sixteen trace elements.

Samples of fly ash sluice water representing an ash to water ratio of 0.03 from the three plants were analyzed for 24 water quality parameters, including 16 trace metals. The fly ash sluice water from Paradise was acid; Kingston, neutral; and Colbert, alkaline. The acidic and alkaline fly ash sluice waters were then adjusted to pH levels of six and nine, and the neutral fly ash sluice water was adjusted to a pH of nine only. The quantities of chemicals required for adjusting pH were proportionate to the ash to water ratio. After pH adjustment and analysis, trace element concentrations were found to be greater than the minimum detectable amount in the original samples.

Quantitative data from the various analyses will be provided in the next annual report.

5.1.4.3 Design of Monitoring Program for Ash Pond Effluents

This study includes the evaluation of an ash pond monitoring program to define the sampling necessary to obtain reliable qualitative and quantitative information.

Data from a preliminary survey performed at Colbert during October 1975 was reported. Pond profiles on the first two days of the initial survey showed the pond to be stratified with respect to temperature. A third pond profile on the third (last) day of the survey showed the pond to be completely isothermal. Other characteristics, such as constant dissolved oxygen levels and uniform pH throughout the pond, were observed. Effluent samples from the ash pond and untreated sluice water samples were also collected, and analyses indicated that the suspended solids concentration in the effluent was less than in the untreated sluice water. This observation agrees with an analysis of the weekly untreated water supply effluent data for the period 1974 to 1975. It was reported that Fe, Cu, and Al associated with the suspended solids was less in the effluent than in the original sluice water. The study also showed that Cu, Fe, and Mg dissolved phases decreased in concentration from the influent to effluent, while As, Al, Ca, and Cr increased in the dissolved phase. The concentration of zinc remained relatively unchanged from intake to effluent. The concentration of lead was below the detection limit of 10 $\mu g/\ell$ in the intake and effluent. A net increase in TDS in the effluent was also observed.

Comparison of data for suspended solids, dissolved solids, alkalinity, and pH during the survey with those taken weekly indicated that the daily variation was no greater than the weekly variation. Also, no daily cycles were indicated.

A second survey similar to the preliminary survey was performed at Colbert five months later. By the use of a dye tracer, the detention time of the ash pond was found to be approximately 12 hours. Two more pond profiles were obtained in order to determine the chemical and mixing characteristics of the ash pond. It was found that the ash pond was stratified with respect to temperature on the first day and completely isothermal on the third day. The first day was extremely calm, while the third day was windy. Hence, wind affects the mixing of the pond and, therefore, the detention time. In order to verify the findings of the first survey with respect to the association of metals with suspended solids, samples were collected to determine suspended metals directly. This will allow a more accurate estimate of the suspended metal concentration. Also, the daily variation of suspended solids, pH, and various trace metals for a longer period was obtained.

Samples will be collected weekly (on random days of the week) from the Colbert ash pond for approximately nine months and analyzed for pH, suspended and dissolved solids, and various trace metals.

Initial chemical analyses from the second ash pond survey conducted in February 1976 at Colbert are shown in Table 45. After the results were obtained, samples footnoted in Table 45 were analyzed for suspended metals or dissolved metals based on total metal concentration and suspended solids concentration. When either suspended solids concentrations or total metal concentrations were low, suspended metals were not analyzed. The samples footnoted were chosen for suspended metal analysis. Only 4 of the 16 effluent samples were analyzed due to the low suspended solids concentration in the effluent.

The data in Table 45 confirmed the finding of the first ash pond survey at Colbert. That is, the total metals concentration does not vary significantly on a daily basis. On that basis, a weekly sampling program was initiated at Colbert with samples collected on a random day of each week.

The preliminary data available to date from 16 weeks of the weekly sampling program are shown in Table 46. Because the data did not show much variation on a weekly basis, sample analysis was further reduced and performed on a biweekly basis as of October 7. Samples are to be collected weekly, but stored in the event the data for the fall and winter months show a greater variation than the previous data. To date, no samples from this program have been analyzed for suspended metals because of the extremely low suspended solids concentrations (usually below 6 mg/ℓ) encountered in the effluent.

5.1.4.4 Chlorinated Once-Through Condenser Cooling Water Discharge Study

The objective of this study is to quantify and evaluate chlorinated effluent from once-through cooling systems.

A preliminary study was initiated at the Kingston steam plant to identify free and total residual chlorine levels in the discharge waters resulting from the chlorination of the condensers on the plant's nine units. Concentration as a function of time was determined for free and total residual chlorine for samples collected at the outlet of the condenser discharge water box on Units 1, 3, 5, 7, and 9. Samples were taken of intake water and were analyzed for total organic carbon, total carbon, total nitrogen, ammonia

TABLE 45. COLBERT ASH POND EFFLUENT SURVEY

February 1976

Sample No.	Date	Time	Sample Location	Solids			Diss. Sulfate, mg/l	Diss. Silica, mg/l	Chromium, µg/l	Lead, µg/l
				Susp., mg/l	Diss., mg/l	Total mg/l				
1	2/18/76		Intake	54	100	154	13	5.0	<5	<10
2[a]	2/19/76	9 a.m. - 2 p.m.	Intake	15	90	105	12	5.0	<5	<10
3[a]	2/20/76	8 a.m. - 2 p.m.	Intake	16	90	106	6	4.8	6	22
4	2/22/76		Intake	8	110	118	18		<5	<10
5[a]	2/23/76	8 a.m. - 2 p.m.	Effluent	8	230	238	87	6.9	7	<10
6	2/23/76	2 p.m. - 8 p.m.	Effluent	4	230	234	87	7.2	19	<10
7[a]	2/23-24/76	8 p.m. - 2 a.m.	Effluent	3	220	223	87	6.6	15	<10
8	2/24/76	2 a.m. - 8 a.m.	Effluent	4	220	224	87	6.3	<5	<10
9[a]	2/24/76	8 a.m. - 2 p.m.	Effluent	5	200	205	89	6.6	11	<10
10	2/24/76	2 p.m. - 8 p.m.	Effluent	7	200	207	89	6.3	<5	<10
11	2/24-25/76	8 p.m. - 2 a.m.	Effluent	4	210	214	92	6.6	10	<10
12	2/25/76	2 a.m. - 8 a.m.	Effluent	3	200	203	92	6.5	7	<10
13	2/25/76	8 a.m. - 2 p.m.	Effluent	3	210	213	92	6.3	23	<10
14	2/25/76	2 p.m. - 8 p.m.	Effluent	2	220	222	94	6.3	17	<10
15	2/25-26/76	8 p.m. - 2 a.m.	Effluent	2	210	212	92	6.3	10	<10
16	2/26/76	2 a.m. - 8 a.m.	Effluent	<1	200	200	92	6.3	23	<10
17	2/26/76	8 a.m. - 2 p.m.	Effluent	<1	200	200	89	6.5	36	<10
18[a]	2/26/76	2 p.m. - 8 p.m.	Effluent	8	210	218	94	6.4	14	<10
19	2/26-27/76	8 p.m. - 2 a.m.	Effluent	<1	200	200	94	6.1	8	<10
20	2/27/76	2 a.m. - 8 a.m.	Effluent	2	200	202	85	6.7	19	<10

NOTE: All metals are total metals.

[a] Chosen for suspended metal analysis.

TABLE 45. COLBERT ASH POND EFFLUENT SURVEY (Continued)

Sample No.	Calcium, mg/l	Copper, mg/l	Iron, mg/l	Manganese, mg/l	Magnesium, mg/l	Zinc, mg/l	Aluminum, mg/l	Arsenic,[a] µg/l	pH	TDS,[b] mg/l	Temp, °C
1	22	0.02	1.7	0.07	3.1	0.03	2.4		8.0	91	
2[c]	21	0.02	1.3	0.05	3.2	0.03	1.6		7.9	85	
3[c]	21	0.24	2.2	0.33	3.2	0.14	1.6		7.7	85	
4	23	0.05	0.81	0.05	3.4	<0.01	0.9		8.5	90	
5[c]	93	<0.01	0.30	0.04	0.5	<0.01	1.7	5	10.95	330	
6	97	<0.01	0.15	0.03	0.5	0.03	1.7	5	11.0	350	14
7[c]	110	<0.01	0.05	0.02	0.4	0.11	1.6	5	11.23	420	14.5
8	110	<0.01	0.13	0.05	0.4	0.16	1.6	10	11.2	400	13.5
9[c]	100	0.09	0.14	0.02	0.4	<0.01	1.7	5	11.3	385	14.5
10	94	<0.01	0.13	0.01	0.4	0.05	1.7	10	11.3	400	15.5
11	91	<0.01	0.09	0.01	0.4	0.08	1.9	5	11.1	385	14.5
12	95	<0.01	0.21	0.01	0.4	0.04	1.9	5	11.2	400	14.5
13	87	<0.01	0.16	<0.01	0.4	<0.01	2.0	5	11.3	400	14.5
14	92	<0.01	0.26	<0.01	0.4	0.02	2.0	5	11.3	390	15.0
15	93	<0.01	0.10	<0.01	0.4	0.02	2.0	5	11.3	410	15.0
16	98	<0.01	0.08	<0.01	0.4	<0.01	1.7	5	11.3	395	15.0
17	88	<0.01	0.06	<0.01	0.4	<0.01	1.6	5	11.3	390	15.5
18[c]	87	<0.01	0.10	<0.01	0.4	<0.01	2.0	10	11.35	370	15.5
19	90	<0.01	0.09	<0.01	0.5	<0.01	1.9	20	11.3	350	15.5
20	91	<0.01	0.09	<0.01	0.5	<0.01	1.8	20	11.36	385	15.5

NOTE: All metals are total metals.

[a] Based on past data, all intake samples assumed to be less than minimum detectable limit of 5 µg/l.

[b] Field conductivity measurement.

[c] Chosen for suspended metal analysis.

TABLE 46. COLBERT ASH POND EFFLUENT MONITORING SURVEY

Values in mg/ℓ

Tag No.	Turbidity	Al	Ca	Cr	Cu	Fe	Pb	Mg	Mn	Zn	Se	As	Dissolved Si	SO_4	Dissolved Solids	Suspended Solids
5418	-	1.4	54	0.010	<0.01	0.20	<0.010	2.9	<0.01	<0.01	0.018	0.080	5.5	58	210	6
5419	-	2.2	-	0.013	<0.01	0.16	<0.010	0.4	0.02	0.04	0.017	0.014	7.1	72	290	2
5417	-	1.8	32	0.025	<0.01	0.12	<0.010	3.2	<0.01	<0.01	-	0.010	6.5	-	340	1
5420	-	1.8	76	0.008	0.13	0.47	<0.010	0.9	0.05	0.13	0.012	<0.020	5.3	130	300	6
5421	-	1.5	65	0.032	0.02	0.28	<0.010	0.8	0.02	0.02	0.012	0.005	4.9	140	40	6
5422	1.5	1.6	120	0.008	0.22	0.22	<0.010	14.	0.02	0.03	0.015	0.025	5.1	190	280	4
5423	1.1	2.5	230	0.040	0.04	0.26	<0.010	0.5	0.01	0.28	0.018	0.030	5.7	130	370	1
5425	<1.0	2.0	140	0.050	0.05	0.10	<0.010	0.6	<0.01	<0.01	0.015	0.015	6.4	200	390	2
5426	1.6	2.5	130	0.042	<0.01	0.25	0.230	0.7	<0.01	<0.01	0.017	0.015	5.3	220	350	6
5424	<1.0	1.7	150	0.009	0.09	0.13	<0.010	0.4	0.02	0.59	0.011	0.009	6.4	140	300	1
5427	1.4	2.6	120	0.041	<0.01	1.0	<0.010	0.6	0.06	<0.01	0.016	0.020	6.2	190	340	4
5428	-	2.2	130	0.018	0.03	2.6	<0.010	1.5	0.07	0.02	0.017	<0.005	6.6	180	350	4
5429	2.9	3.1	170	0.034	0.02	0.20	<0.010	0.2	<0.01	0.09	0.021	0.015	7.1	180	470	2
5430	2.0	3.2	130	0.021	0.06	0.17	<0.010	0.3	<0.01	<0.01	0.021	0.020	5.3	180	310	10
5431	1.4	2.6	170	0.024	0.11	0.56	<0.010	<0.1	0.11	0.02	0.013	0.015	7.0	200	460	4
5432	1.2	3.1	140	0.018	<0.01	0.23	<0.010	0.2	0.01	0.04	0.019	<0.005	6.8	170	360	<1
5433	2.4	6.1	140	0.021	0.04	16.	0.019	0.2	0.39	0.04	0.015	0.025	5.9	160	370	9
5434	1.2	3.2	170	0.025	<0.01	0.15	0.019	0.2	<0.01	0.06	0.016	0.020	6.4	160	370	17
5436	11.	2.9	140	0.034	0.02	0.29	0.014	0.3	0.01	0.02	0.005	0.025	6.5	-		2
5437	<1.0	2.4	73	0.029	0.02	0.18	0.011	0.2	<0.01	<0.01	0.004	0.020	6.7	160	720	3
5438	-	3.9	280	0.009	0.02	10.	<0.010	4.5	0.23	0.06	0.020	<0.005	7.1	180		2
5439	3.5	3.3	160	0.037	0.02	0.19	<0.010	0.8	<0.01	0.05	0.025	0.010	6.1	200	480	6
5435	2.8	4.8	120	0.034	0.02	0.78	<0.010	0.8	0.04	0.02	0.016	0.015	6.2	230	430	11
5440	2.1	2.2	150	0.027	<0.01	0.38	0.018	0.7	0.03	0.04	0.020	0.012	5.4	220	430	8

nitrogen, chlorine demand, total suspended solids, volatile and nonvolatile chloro-organics, and pH. Also, a sample from the condenser outlet was analyzed for volatile and nonvolatile chloro-organics.

The results of the preliminary study indicated that the intake water had a low nitrogen content and a relatively high pH (7.8 to 8.5). The varying pH was due to a change in the intake water source, depending on the time of year. This pH range results in a 10 to 30 percent HOCl level, which is about 80 times more efficient as a biocide than OCl^-. Because of the high pH and the variability of the intake water, the plant was dropped as the site to perform a detailed chlorination study.

The John Sevier plant was then selected for a preliminary study. On the basis of water quality information and inlet and outlet condenser sample analyses it appeared that the plant intake water came from the same source river and also had a relatively high chlorine demand. Therefore, the plant was retained as a site to be studied in greater detail to test and develop a methodology for assessing minimum effective chlorine dosage for control of biological fouling in steam-electric generating station cooling systems.

Weekly condenser performance tests and free and total residual chlorine measurements will be made at the inlet and outlet of the condenser on each unit, using predefined chlorine feed rates. Also, determination of water quality parameters is planned to try to correlate with the chlorine requirements. Using these data, the study will attempt to develop a methodology for assessing minimum effective chlorine dosage for control of biofouling in the cooling system of a steam-electric generating station. The chlorination rates selected for the four units at John Sevier were as follows:

a. Unit 1 -- 6000 lb/24 hr for 2-hr duration

b. Unit 2 -- 7500 lb/24 hr for 20 min, twice per day

c. Unit 3 -- 4500 lb/24 hr for 20 min, twice per day

d. Unit 4 -- 6000 lb/24 hr for 20 min, twice per day

Unit 4 represents present and past chlorination practice and will be used as a control. At least once per week, water entering the cooling system will be monitored at the intake of each unit for total residual chlorine, at the inlet to each unit for total residual chlorine, and at the outlet of each unit for free residual chlorine.

During initial attemps to chlorinate, problems were experienced with the chlorinators in maintaining the rates indicated above. Therefore, the chlorination study was temporarily halted until a new chlorinator incorporating a flow meter and recorder is procured and installed. Resumption of the study is expected in the near future.

5.1.4.5 The Effect of Coal-Ash Leachates on Groundwater Quality

A field survey was completed at Kingston. Thirteen monitoring wells were installed at eight locations in and around the ash disposal pond. Figure 36 illustrates their approximate positions, and Figure 37 shows a profile of the ash pond substrata. Wells Nos. 1 and 8 function as control wells, while Nos. 2 and 3 and 4, 5, 6, and 7, respectively, are located in the ash pond proper and on the dike.

Continuous soil core samples were taken at all locations, and when possible the soil water was extracted and analyzed in the field for pH, conductivity, TDS, calcium, and sulfate. In addition to the above analyses, 97 soil core samples and 44 water samples extracted from the soil cores are being analyzed for Fe, Cu, Cd, Hg, Zn, Cr, Pb, Al, Ni, Ca, Mg, As, Be, B, and Se. The cation exchange capacity on the soils will be determined. Subsoil samples were collected for physical analyses. Determinations of horizontal and vertical permeabilities of the various strata were conducted along with grain size distribution, dry densities, percent moisture, and soil classification. Soil elution tests are also planned. The data are being analyzed and will be available in the next annual report.

The soils tested generally were of medium to high (89 to 112 pcf) dry density, fine grained, or well-choked with fines, with vertical permeabilities ranging from 6.3×10^{-8} to 6.1×10^{-6} cm/sec and horizontal permeabilities in the range of 7.4×10^{-8} to 7.4×10^{-5} cm/sec.

Transparent plastic columns were packed with soil to a density approximating field conditions, and water taken from well No. 2 in the old Kingston ash pond was leached through the columns. In all tests reported thus far, clogging of the columns occurred. This was due to the precipitation of iron, which was caused by oxidation of the elution water during the experiment. Future testing will be done under anaerobic conditions.

Monitoring well and soil sampling at Widows Creek has not been completed. A total of 19 monitoring wells has been installed. These include nine ash pond sites, two control sites, and eight scrubber pond sites (five for trace metals and three for organics). Results of the soils analysis will be provided in the next annual report.

5.1.5 Fly Ash Characterization and Disposal (TVA)

The objectives of this interagency-funded program with TVA, Power Research Staff, Chattanooga, are to characterize chemically and physically coal-fired boiler ashes and waste effluents. In addition, studies on fly ash handling systems disposal and utilization of fly ash, and treatment methods for water reuse and recycle will be conducted. Work was initiated in June 1975, and the final report on the project is planned for December 1979.

Data since the last report from TVA progress reports on the characteristics of ash have been summarized and evaluated. Also, chemical and physical analyses of coal, coal ashes, and ash effluents

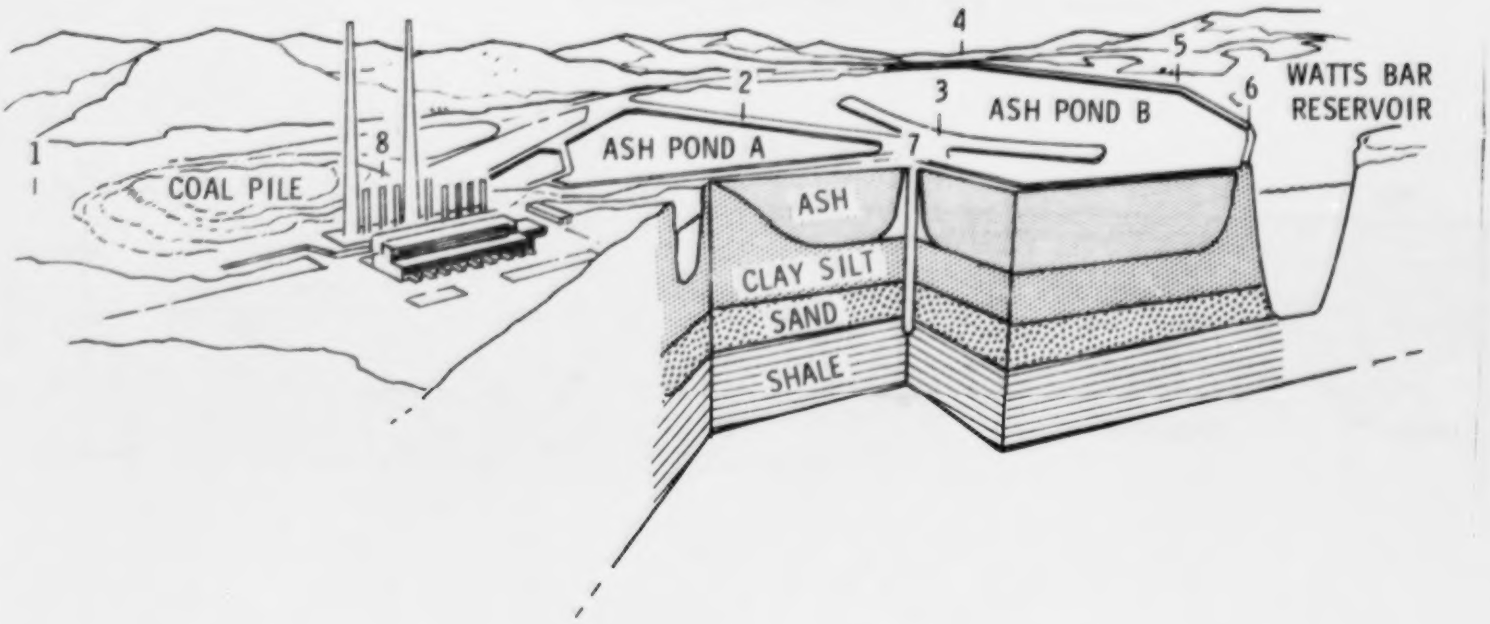
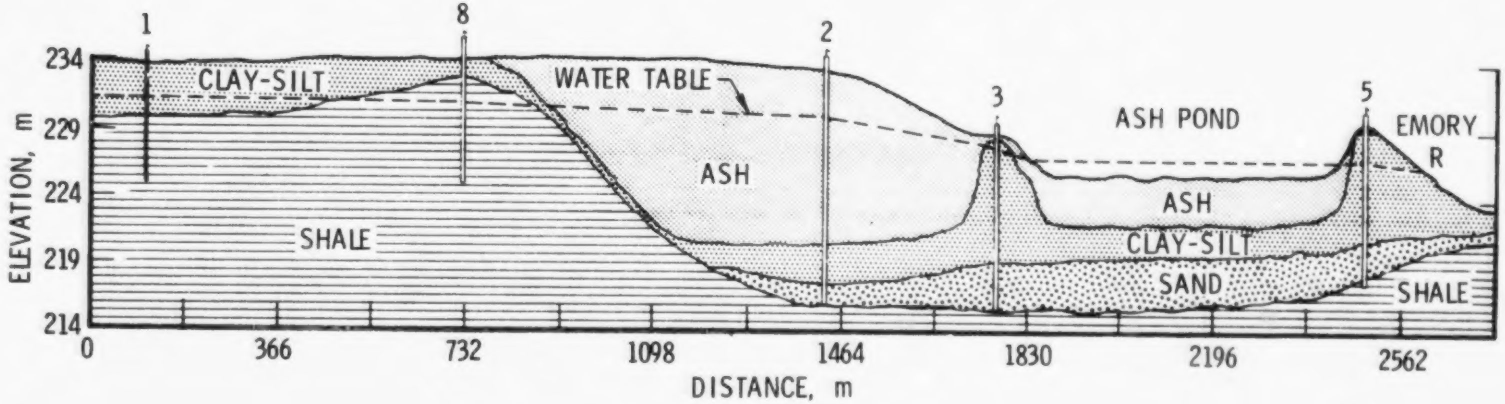

1
COAL PILE
8
2
ASH POND A
4
3
7
ASH POND B
5
6
WATTS BAR
RESERVOIR
ASH
CLAY SILT
SAND
SHALE

Figure 36. Spatial distribution of monitoring wells at the Kingston generating facility.



1
8
2
3
5
234
229
224
219
214
ELEVATION, m
CLAY-SILT
WATER TABLE
ASH
SHALE
ASH POND
ASH
CLAY-SILT
SAND
SHALE
EMORY R
0
366
732
1098
1464
1830
2196
2562
DISTANCE, m

Figure 37. Topographic profile illustrating wells and soil strata.

are being conducted at the Colbert plant and are planned for the Kingston plant in order to characterize these materials at two different plants having different boiler designs and burning different types of coal. The various methods available for disposal and utilization of fly ash may also be evaluated, depending on fuel availability. The first phase of the program, scheduled for completion in June 1978, will conclude with a summary of information on physical and chemical processes for reusing or recycling sluice water.

Studies of dry and wet ash handling systems may be conducted, and recommendations may be made relative to the more promising systems for ash handling, disposal, and utilization alternatives.

The TVA plants at Colbert and Kingston have been selected for conducting chemical analyses of the streams. Complete stream characterization will be conducted initially for the Colbert plant only (Figure 38). Some of the work is being performed under another project, "Characterization of Effluents from Coal-Fired Power Plants," reported in Section 5.1.4.

In order to develop sampling procedures and methods, preliminary sampling programs were conducted at the Colbert steam plant. Sampling sites included the coal scales, pulverizers, mechanical collector, electrostatic precipitator (ESP), and pyrite hoppers and their respective ash slurry streams. Laboratory analyses being performed on samples from the various streams are listed in Table 47. Some sampling problems were experienced, primarily with various outages of plant equipment. Modifications in procedures as a result of the preliminary sampling program were devised.

Conclusions derived from analysis of data from the preliminary sampling program include the following:

a. Chemical analyses for Ca, Fe, S, Al, and Si were generally consistent in all samples collected.

b. Zn and Cu showed considereable variation between all samples collected during a three-day sampling period.

c. Variability of the five major species between bottom ash and mechanical ash slurry were attributed to poor communication between power plant and sampling personnel and inadequate flushing of sluice lines between sample collections.

d. The five primary constitutents (if assumed to be in the oxide state) accounted for about 90 percent by weight of the ash.

e. Mass balances relative to incoming coal and slurry streams were Al, – 2 percent; Ca, + 35 percent, Fe, + 43 percent; Si, + 25 percent and S, - 98 percent (lost to stack). The major unbalances were attributed to difficulty in sampling solids in the two-phase slurry flows.

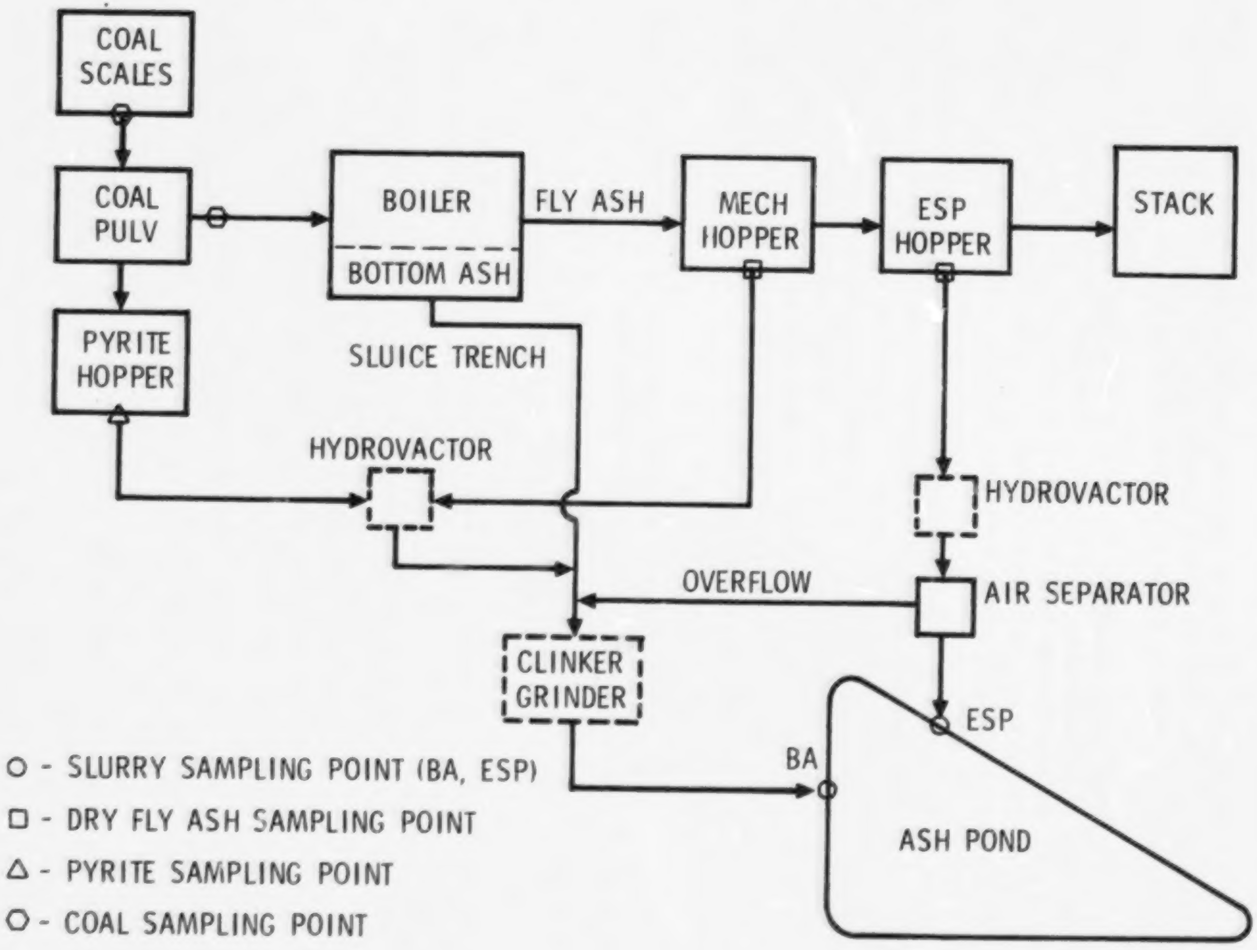

COAL SCALES
COAL PULV
PYRITE HOPPER
BOILER
BOTTOM ASH
FLY ASH
MECH HOPPER
ESP HOPPER
STACK
SLUICE TRENCH
HYDROVACTOR
HYDROVACTOR
OVERFLOW
AIR SEPARATOR
CLINKER GRINDER
BA
ESP
ASH POND
○ - SLURRY SAMPLING POINT (BA, ESP)
□ - DRY FLY ASH SAMPLING POINT
△ - PYRITE SAMPLING POINT
⬡ - COAL SAMPLING POINT

Figure 38. Schematic diagram of sampling locations for coal and ash at Colbert Steam Plant Unit 1.

TABLE 47. SAMPLE ANALYSES

Laboratory		
Samples	Parameters Analyzed for Each Sample	
Pulverized Coal (dry)	Aluminum (Al)	Lead (Pb)
Pyrite (dry)	Antimony (Sb)	Magnesium (Mg)
Electrostatic Precipitator Fly Ash (dry)	Arsenic (As)	Manganese (Mn)
Mechanical Collector Fly Ash (dry)	Barium (Ba)	Mercury (Hg)
Bottom Ash (BA) Slurry	Beryllium (Be)	Nickel (Ni)
Settled Solids (14 hr)	Boron (B)	Potassium (K)
Water	Cadmium (Cd)	Selenium (Se)
Suspended	Calcium (Ca)	Silicon (Si)
Dissolved	Chloride (Cl)	Sodium (Na)
Inflow Water	Chromium (Cr)	Sulfate
Suspended	Cobalt (Co)	Titanium (Ti)
Dissolved	Copper (Cu)	Vanadium (V)
	Fluoride	Zinc (Zn)
	Iron (Fe)	
Pyrite	True Specific Gravity	

Field	
BA Slurry	Temperature
Inflow Water	pH
	Conductivity
	Phenol Alkalinity
	Total Alkalinity
	ORP

Improved definition in the data reported here and additional data are anticipated as full-scale sampling procedures are improved.

A draft of the work plan and experimental design for the task to investiage physical and chemical processes for recycling or reusing of ash sluicing water has been prepared.

The report "Characterization of Ash from Coal-Fired Power Plant" is in publication and is expected to be available early in 1977. Its purpose is to present a summary of existing data on the chemical and physical characteristics of ash produced by the burning of coal in steam-electric generating plants. Several recent studies concerned with the characteristics of coal, ash, or ash effluents were examined. The focus included the elemental chemical composition of the coals and their ashes, with emphasis on the trace inorganic constituents and toxic elements. Methods for the chemical analysis of ash and coal matrices were examined to aid the evaluation and comparison of results from studies performed with different analytical methods. The finer particulates are a particular source of concern because they have higher concentrations of potentially hazardous trace elements, pass through collection devices, and are emitted to the atmosphere in greater proportions than larger particles.

Results from analytical studies of power plant residues were found to be not always comparable because of differences in analytical methods used in determining the various elements and in sample preparation and handling. These sources of error are in addition to the normal inter-laboratory dispersion present when multiple institutions determine the same sample by identical preparation and analytical techniques. Recommendations were made to develop standard analytical practices for trace elements in the coal and ash matrices.

In evaluating the analytical studies of coal and its combustion residues, the various sources were regarded as being generally agreed that elements are partitioned into three main groups with respect to their distribution in the residues:

a. Group I -- Elements which are approximately equally distributed in the bottom ash and the fly ash

b. Group II -- Elements which are preferentially concentrated in the fly ash as compared to the bottom ash

c. Group III -- Elements which are primarily emitted to the atmosphere as gaseous species

The theory for this partitioning effect involves the volatilization of some elements or their compounds in the furance. Later, these vaporous phase elements recondense completely or partially or are discharged through the stack as gases. Elements with higher volatilization temperatures than that reached in the boiler remain about evenly distributed in the two ash fractions

(Group I). Others are volatilized and are not cooled sufficiently to condense (Group III). Elements which do condense generally form fine particles or are deposited onto the surface of small particles (Group II).

5.1.6 Studies of Attenuation of FGC Waste Leachate by Soil (U.S. Army Development & Readiness Command)

The U.S. Army Development and Readiness Command (DARCOM), formerly Army Materiel Command, Dugway Proving Ground, Utah, is conducting a study to determine the extent to which heavy metals and other chemical constituents of FGC wastes migrate through soil in land disposal sites. The experimental FGC program was initiated in December 1975 and will be completed October 1977. The project consists of the following tasks: (1) physical and chemical characterization of wastes, (2) flow rate studies, and (3) soil column studies.

Six FGC wastes and three fly ash wastes are being applied to six soils to observe any changes in the physical and chemical properties of the soils and to quantify the migration of the waste constituents through the soils. All experimental work and the final report on this group of 9 wastes is scheduled for completion 24 months after collection of the last waste. An interim progress report will be published in 1977 covering work through the end of calendar year 1976.

The FGC wastes and soils are identified and summarized in Tables 48 and 49.

5.1.6.1 Waste Characterization

Chemical composition of the wastes are being determined prior to their application to the soil columns. Characterization of the wastes will include pH, conductivity, TDS, major cations and anions, fluoride ion and trace metal concentrations.

An analysis of each waste is shown in Table 50. These are based on digestion of one gram of dry (to constant weight at 105°C) waste with concentrated hydrochloric and nitric acids. Beryllium and selinium were not detected. Analysis for boron, fluoride, calcium, magnesium, sodium, and silicon is planned.

The concentration of the various constituents in the FGD waste supernate are shown in Table 51. Although the Fe content is high in the wastes, it is apparently present in insoluble forms as evidenced by the low concentration in the liquor. Lead appears to be leached from the wastes more consistently than the other metals. Arsenic and zinc were present in significant concentrations in some of the liquors.

The solubilization of a number of constituents as a function of the pH was determined. Ten and 20 percent samples, i.e., 20 and 40 grams of dry waste per 200 mℓ of water were titrated with 1.0 N HNO_3 and 1.0 N NaOH, as appropriate, to adjust the pH of the solutions to 5, 7, and 9

TABLE 48. FGD WASTE CHARACTERISTICS

Designation	Source	Conditions during FGD Waste Sample Collection						pH
		Absorbent	Coal		Solids Content, %	Sampling Location	Date	
			Type	% S				
A	Commonwealth Edison Co., Will County Station	Limestone	Wyoming	NAV[a]	40-50[b]	Thickener underflow	15 Oct 1975	10.4
B	Duquesne Light Co., Phillips Power Station	Lime[c] (dolomitic)	Eastern	2.2	NAV[b]	Thickener underflow	20 Oct 1975	8.8
C	General Motors, Parma	Double Alkali (soda ash and lime)	Ohio	2.5	~50[b]	Filtered solids	21 Oct 1975	11.1
D	Arizona Public Service Co., Cholla Station	Limestone	New Mexico	0.3-0.6	12-15[b]	Scrubber discharge	27 Feb 1976	6.2
E	Kansas City Power and Kansas Gas and Electric, La Cygne Station	Limestone	Missouri	NAV	~15%	At pond near scrubber discharge outfall	22 Mar 1976	10.4
F	TVA, Shawnee	Lime[d]	So. Illinois	NAV	NAV	From disposal site	24 Mar 1976	NAV

[a] Not available.

[b] Including fly ash.

[c] Normally high calcium is used.

[d] Being used on collection date.

TABLE 49. SOILS CHARACTERISTICS

Source	Soils Classification/Characteristics			
	Type	Class	% Clay	Water Penetration, cm/sec
North Carolina, Davidson series	Clay	Ultisol	>60	$\approx 10^{-2}$ to 10^{-5}
Indiana, Chalmers series	Silty loam	Mollisol	>90% silt and clay	$\approx 10^{-5}$ to 10^{-7}
Kentucky, Nicholson series	Silty clay	Alfisol	>95% silt and clay	$\approx 10^{-5}$ to 10^{-7}
Shawnee Kentucky (fill soil)	NAV	NAV	NAV	NAV
Dugway Utah, Sample 1	NAV	NAV	NAV	NAV
Sample 2	NAV	NAV	NAV	NAV

NAV denotes not available at present.

TABLE 50. CONCENTRATION OF VARIOUS METALLIC CONSTITUENTS IN FGD SOLIDS

Source of Waste	Concentration in mg/kg									
	As	Be	Cd	Cr	Cu	Ni	Pb	S	Zn	Hg[a]
Plant A	900	<200	700	2500	4400	2700	17700	<1000	23200	4
Plant B	13000	<200	<200	600	1700	1900	6700	<1000	4700	11
Plant C	17700	<200	300	1100	2600	2100	17000	<1000	10300	43
Plant D	2000	<200	300	1500	2400	2100	12300	<1000	5000	6.7
Plant E	2200	<200	1400	500	1800	3100	15300	<1000	62300	3.5
Plant F	6700	<200	400	2300	2700	2600	900	<1000	14900	2

[a] Permangante digestion.

NOTE: Beryllium and selenium were not detected.

TABLE 51. CONCENTRATION OF VARIOUS METALLIC CONSTITUENTS IN FGD SOLID SUPERNATE

Source of Waste	Concentration in mg/ℓ													
	As	Ca	Cd	Cr	Cu	Fe	Hg	K	Mg	Na	Ni	Pb	Si	Zn
Plant A	0.09	560	<0.02	<0.05	<0.02	<0.05	<0.002	167	1.9	1200	0.07	0.10	2	0.03
Plant B	0.35	465	0.02	0.08	0.04	0.07	<0.002	120	2300	85	0.08	0.35	5	0.04
Plant C	<0.05	645	<0.02	0.09	<0.02	<0.05	<0.002	34	0.32	610	0.05	0.14	5.5	0.02
Plant D	<0.05	670	<0.02	0.05	<0.02	0.05	<0.002	15	195	1000	0.17	0.15	22	0.48
Plant E	0.10	785	<0.02	<0.05	0.03	0.05	<0.002	55	3.5	58	0.07	0.10	6.5	0.04
Plant F	<0.05	4370	0.03	<0.08	0.06	0.13	<0.002	90	4.5	98	0.16	0.45	4	0.04

(Table 52). As expected, the solubility of the metals generally increased as the pH decreased. Analyses from plants D, E, and F are being performed.

5.1.6.2 Flow Rate Studies

In addition to examining the potential for migration of hazardous substances from the FGD and fly ash wastes, any chemical and/or physical interaction which may take place between the wastes and the natural clay soils used in the investigations will be determined. Any interactions between the soils and wastes could affect the suitability of such soils at disposal sites. Nine wastes using six soils with three replications are being applied to 162 soil columns. Visual observation of the soils will be made, and flow rates will be measured to record any changes in soil permeability resulting from possible interactions with the wastes.

Prior to conducting tests where the waste is placed on the soil, soil-only and waste-only flow characteristics were conducted.

5.1.6.2.1 Soil-Only Flow Characteristics

Soil columns were prepared by placing a small piece of glass wool in the bottom of the glass container. Thirty grams of white, washed quartz sand were placed over the glass wool, and the soil was added in 10-gram segments until the desired height was attained. Each additional soil segment was tamped 10 to 15 times to pack the soil column to the desired density of 1.5 g/cc.

Initially several soil columns of each soil were prepared and leached to develop a procedure that would produce desired flow rates of 100 to 400 mℓ /day for each column. A variation of approximately 100 to 150 mℓ /day between replicates of one soil type was deemed acceptable. Difficulty was experienced in packing the soil columns to a bulk density of 1.5 g/cc when dry soil was used. Further, the flow rates of dry soil columns of the same soil varied considerably. It was concluded that more reproducible results would be obtained if the soils were moistened slightly before being compacted.

The flows obtained when Davidson, Chalmers, and Nicholson soils were compacted at different initial water contents varied greatly. However, after some experimentation it was determined that Davidson and Chalmers soils containing 16 percent water and Nicholson soil containing 13 percent water resulted in achieving flow rates within the criterion established. A six-foot head of water was maintained on all columns. The soil column tubes are 1-1/2-inch inner diameter and 16-inch long sections of glass. Soil depth was established as approximately 50 mm.

5.1.6.2.2 Waste-Only Flow Characteristics

The flow rates for columns containing waste only were also measured. Results from two samples from each of the six plants were reported. It was observed that periodic channeling occurred with resultant

TABLE 52. SOLUBILIZATION OF METALS AND CHLORIDES FROM FGD WASTES

Source of Waste	pH of Waste	Grams Waste to 200 ml Water	pH, Adjusted	Concentration of Constituents (mg/ℓ)											
				Cd	Cr	Cu	Fe	Ni	Pb	Zn	Ca	Mg	Na	Si	Cl
Plant A	10.4	20	5.0[a]	0.21	0.20	0.26	0.34	0.80	1.4	2.4	6700	136	350	11	104
		40	5.0[a]	0.22	0.44	0.50	0.76	1.4	3.1	1.8	19500	290	650	7	273
		20	7.0	0.03	<0.05	0.04	0.08	0.14	0.30	0.07	1300	28	335	5	103
		40	7.0	0.03	0.06	0.06	0.10	0.15	0.40	0.07	2000	56	465	5	196
		20	9.0	<0.02	<0.05	<0.02	<0.05	<0.05	0.10	<0.02	410	2.4	330	2	98
		40	9.0	<0.02	<0.05	<0.02	<0.05	<0.05	0.10	0.03	420	4.5	490	<1	218
Plant B	8.8	20	5.0	0.03	<0.05	0.10	34	0.29	0.20	0.31	670	730	220	38	271
		40	5.0	0.03	<0.05	0.08	45	0.46	0.30	0.38	750	1380	260	46	550
		20	7.0	<0.02	<0.05	0.02	0.05	0.10	0.20	0.04	550	740	170	8	302
		40	7.0	0.03	<0.05	0.03	0.07	0.10	0.30	0.04	500	1410	190	8	642
		20	9.0	0.02	<0.05	<0.02	0.05	0.06	0.20	<0.02	340	600	290	3	309
		40	9.0	0.02	<0.05	<0.02	0.05	0.07	0.20	0.03	310	960	305	3	528
Plant C	11.1	20	5.0	0.06	0.08	0.14	1.8	0.65	0.60	3.00	2800	250	610	50	43
		40	5.0	0.11	0.14	0.19	7.2	1.10	1.00	4.40	4450	480	575	25	88
		20	7.0	0.02	<0.05	0.04	0.10	0.15	0.40	0.02	1870	50	505	7	66
		40	7.0	0.03	0.07	0.07	0.14	0.20	0.60	0.04	2520	73	700	9	109
		20	9.0	<0.02	<0.05	<0.02	0.06	0.06	0.10	<0.02	570	8.6	465	7	65
		40	9.0	<0.02	<0.05	0.02	0.08	0.08	0.20	0.02	870	20	790	9	130

[a] Never reached a stable reading of pH 5. Solution stabilized at pH 5.6.

rapid increases in flow rates. Examples of this characteristics are shown in Figures 39 and 40. The figures are typical plots of the flow of water through columns of wastes. Large increases in flow through the wastes are particularly noticeable in Plants A, B, C, and D. When the flow exceeded 500 mℓ /day, the waste columns were stirred to break the channels in the wastes. The flow would immediately decrease. However, new channels would form, and the flow rate would again increase. Because of the ease and continual formation of channels in the wastes from Plants A and D, these columns flow studies were terminated.

The occurrence of channeling and stirring for wastes A, B, and C are shown in Table 53. The resultant decreases in waste depths are also shown.

TABLE 53. CHANNELING OCCURRING WASTE-ONLY COLUMNS AND DECREASE IN WASTE COLUMN DEPTH

Sample	Occurrence of Channeling, Days After Start of Test	Decrease in Depth, mm	Percent Decrease in Depth
Plant A	6, 22, 39	25	13
Plant A	6, 20, 39	25	13
Plant B	4, 25	1	4
Plant B	8, 30	1	4
Plant C	38	15	8
Plant C	--	1	5

The flow studies in which Plants A, B, C, and D waste were applied to Davidson soil were terminated in June (except for one Plant B column). The soil from these columns was saved for chemical analysis. It was noted that after the wastes that exhibited channeling from Plants A and C above the Davidson soil columns were stirred, the flow of water through the soil columns was greatly reduced. However, the flow rates returned in a few weeks to the previous rates, indicating rapid formation of channels through the waste.

5.1.6.2.3 Waste and Soil Flow Characteristics

The effect of wastes on the flow characteristics varied, and in some cases the presence of waste on the soil affected the flow significantly. Increases in the flow through Davidson soil after it was treated with wastes from Plants A, B, C, and D was significant. The wastes from Plants A, C, and D produced a large increase in two to four weeks. An example from plant A is shown in Figure 41. The wastes from Plant B produced nearly an immediate effect upon two of the soil columns; however, the increase in the third was gradual (Figure 42). The wastes from Plants E and F have produced little effect upon the infiltration rate in the two months the wastes have been in contact with the soil (Figure 43).

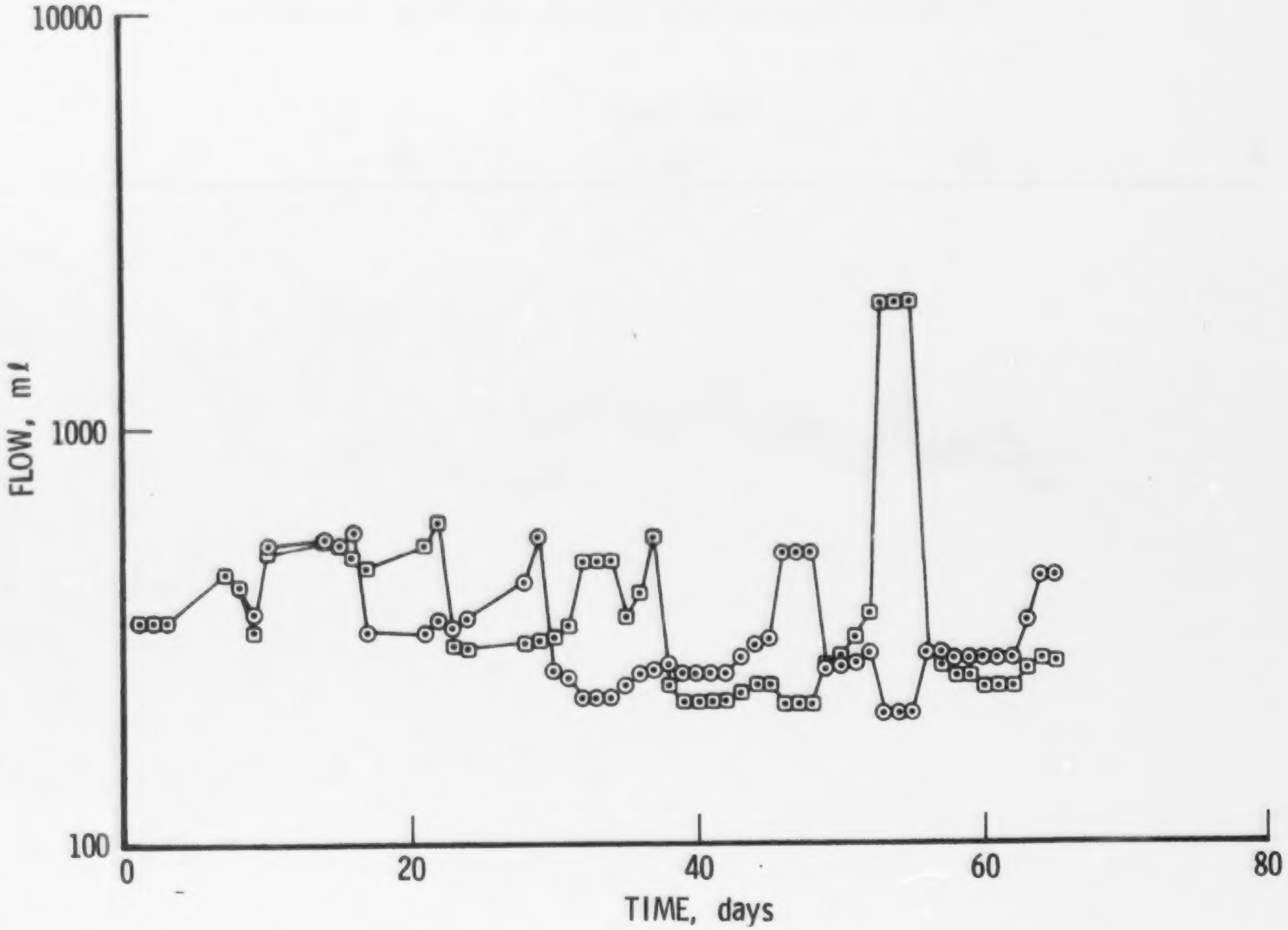


Figure 39. Flow rate of water through Plant A FGD waste.

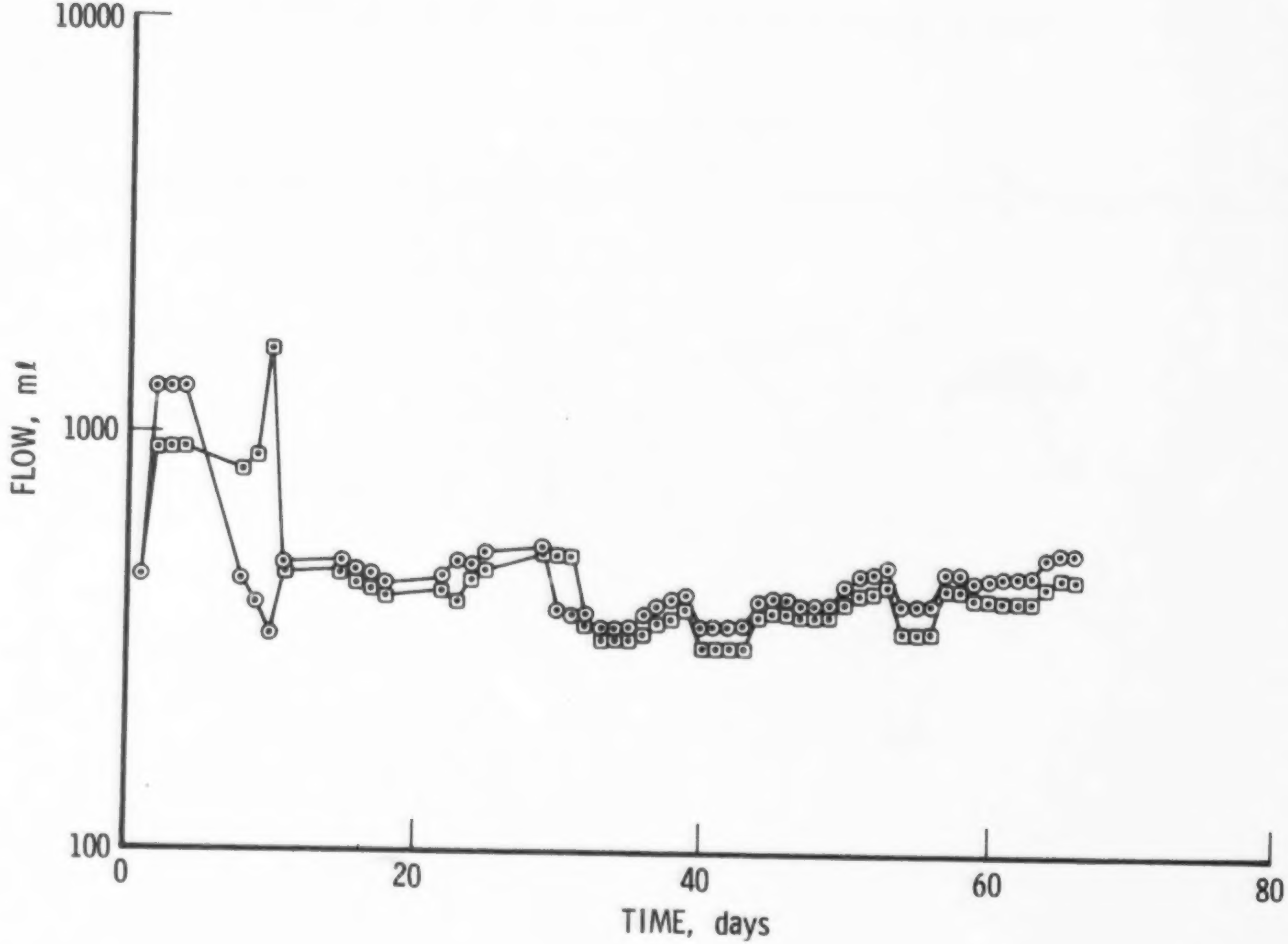


Figure 40. Flow rate of water through Plant B FGD waste.

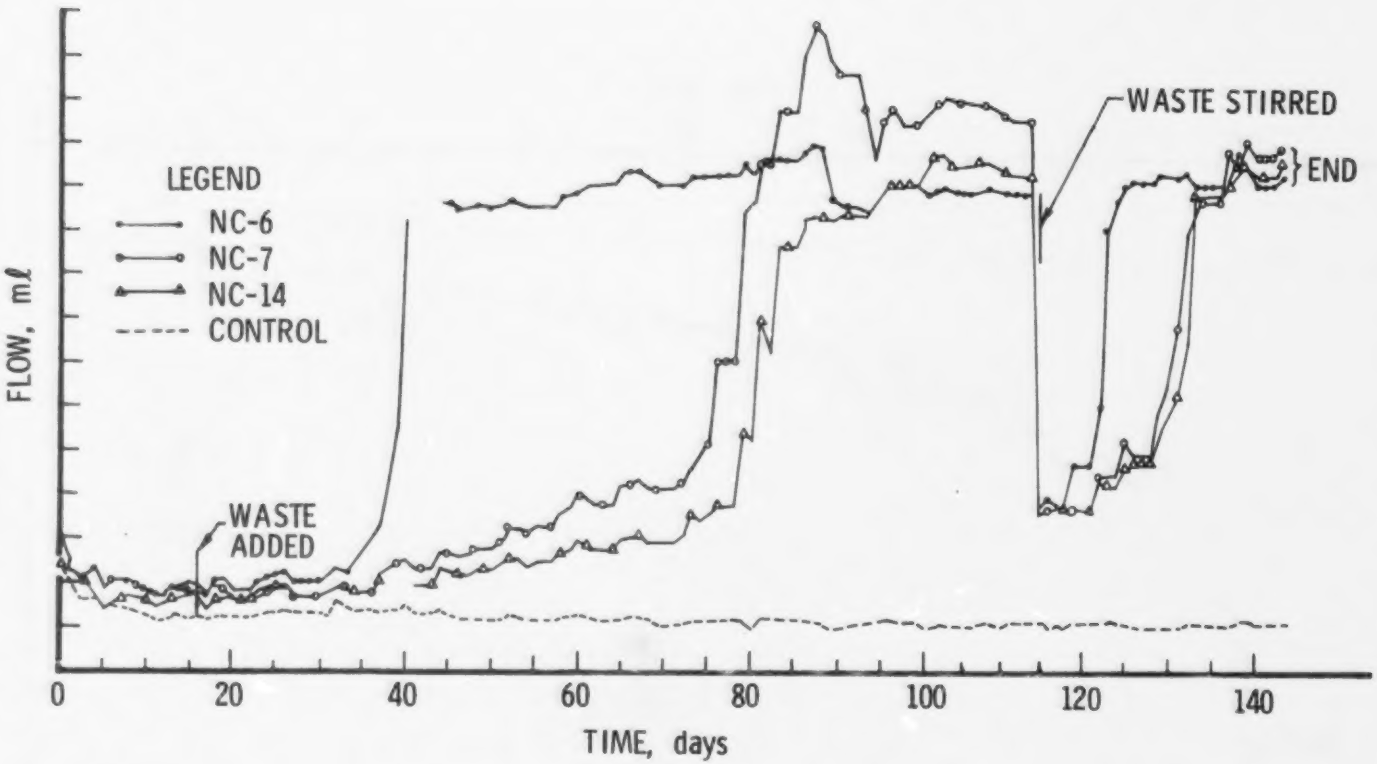


Figure 41. Effect of plant A waste on the flow rate of water through Davidson soil.

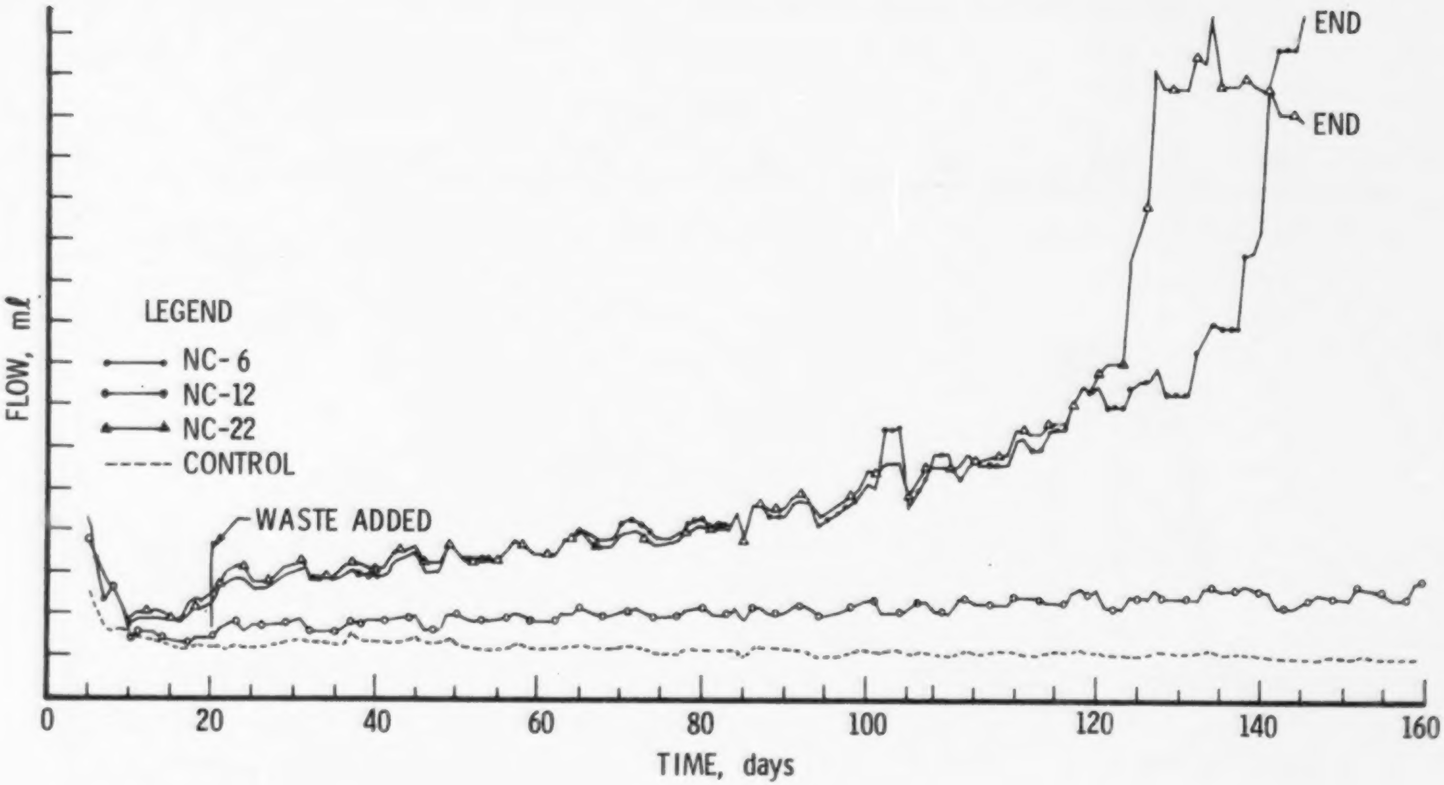


Figure 42. Effect of Plant B waste on the flow rate of water through Davidson soil.

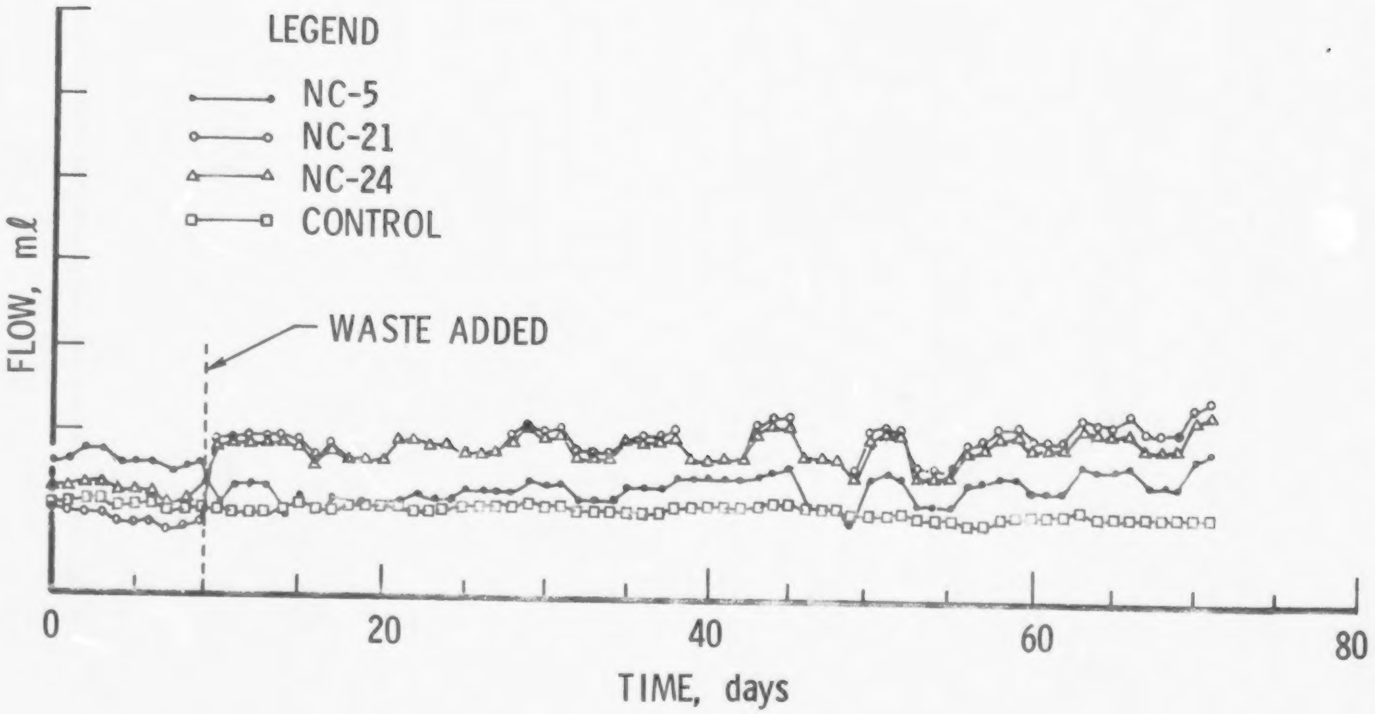


Figure 43. Effect of Plant F waste on the flow rate of water through Davidson soil.

Wastes from Plants A, C, and D caused an increase in the flow of water through Chalmers soil. However, the increase in flow rates was not as dramatic as was observed with the Davidson soil. Also, the flow of water through the Chalmers control columns tended to be more variable than the Davidson control columns. Wastes E and F are expected to be tested shortly.

Nicholson soil columns which have been flowing for less than two months (except for Plant B waste soil columns which were in test about four months) have produced little effect upon the infiltration rate with any of the six wastes.

The infiltration of water through Kentucky soil after treatment with each of the six FGD wastes showed no significant change in flow rate in approximately three months of exposure.

5.1.6.3 Column Migration Studies

Soil column studies are being conducted to monitor the movement in soil of contaminants leached from the FGD and fly ash wastes. Compounds of arsenic, beryllium, cadmium, chromium, copper, mercury, lead, zinc, and fluorides may be present in the soil column leachate. FGD and fly ash wastes are being applied to 162 soil columns. Each of nine wastes (six FGD and three fly ash) will be applied to six soils with three replications of each combination. Leachate migrating through the columns will be analyzed for the preselected anions or cations present in the waste. Provisions in the construction of the columns will permit sampling of the liquid at both the interface between the soil and the wastes and at the base of the column.

When one or more of the compounds are found in the soil column effluent, one of the three columns (each combination of waste and soil is replicated three times) will be removed, sectioned, digested and/or extracted, and each section analyzed for the compounds of interest. This process will provide information relative to distribution and mobility of the compounds through the soil with time. The remaining two columns will continue to be leached until one or more additional compounds are detected in the effluent. At the time of the second "breakthrough," one of the two remaining columns will be taken down, sectioned, and analyzed as previously described. The last remaining column will be treated with fresh waste and the leaching continued until a significant change is found in the composition (pH, conductivity, and/or concentration of metals breaking through the column) of the effluent.

Leachate samples from the flow rate columns were collected and were analyzed with emphasis being given to the samples collected from the Davidson soil waste columns. This was done in order to gain some insight as to the migration of metals through the soil and to assist with the design of full-scale migration columns.

Analysis of the leachate during the first month of soil exposure to the waste showed that metals in the leachate decrease to or below the detection level of the analyses. Initially Ni, Pb, and Zn concentrations were significant but decreased to the detection limit within two months. As, Be, Cd, Cr, Cu, and Se were always below the detection limit. K, Mg, and Na were very high initially but rapidly decreased to a low but detectible level. Ca remained high throughout the experiment although some decrease was observed.

Any conclusions regarding the attenuation of Davidson soil would be premature at this time inasmuch as the results reported were from data when the column flow rate had not been disrupted by an increase in flow rate as a result of channeling in either the waste or soil.

5.1.7 Compilation of Data Base for the Development of Standards and Regulations Relating to Land Disposal of FGC Sludge (SCS Engineers)

A study was initiated in December 1975 with SCS Engineers, Long Beach, California, to establish a data base for use by EPA in its development of FGD waste disposal standards. The final report is currently in publication, and its availability is expected in the near future.

The data base compilation performed in Phase I of the study included a categorization of the power generating industry and the location of FGD waste sources, the state of the art of FGD system control technology, untreated and treated waste characterization, and the current practices in sludge treatment and disposal technology.

In addition, the forthcoming Phase II report will address such factors as site characterization, health effects, safety, ecological effects, and land use and aesthetics in its environmental considerations of FGD sludge disposal (Table 54). Existing and proposed federal and state regulations, that may apply to the disposal of FGD wastes are summarized and discussed. Potential chemical and physical regulating parameters are identified.

The conclusions drawn about the environmental impact of FGD disposal were limited because of the broad range of information being obtained and not yet reported. Significant observations and generalizations resulting from the Phase I study are outlined here:

a. A potential exists for catastrophic environmental impact on surface water resources from a dike failure at a pond containing FGD sulfite sludges. The oxygen demand exerted by these sludges is sufficient to destroy aquatic life for long distances. Regulations pertinent to siting and construction of FGD sludge disposal sites should be sufficiently stringent to provide assurance against massive accidental discharges. Existing state and federal regulations on pond and dike construction for phosphate sludges and acid mine drainage sludges were recommended as a starting point for development of suitable FGD sludge regulations.

TABLE 54. CONTENT OF FINAL REPORT

- Industry Categorization
    - Description of Power Generation Utilities
    - Location of FGD Users
    - Existing FGD Systems and Sludge
- Control Technology
    - State of the Art
    - FGD Systems with Sludge Generation
    - Control Processes, without Sludge Generation
- By-Product Recovery Systems
    - Marketable Products
    - Use as an Additive
    - Specialty Uses
- Waste Characterization
    - Characterization Parameters
    - Chemical and Physical Characteristics
- Treatment and Disposal Technology
    - Current Practices
    - Unstabilized
    - Stabilization Methods
- Cost of Disposal Options
    - Cost of Unit Operations
    - Cost of Typical Systems

TABLE 54. CONTENT OF FINAL REPORT (Continued)

- Environmental Considerations
    - Site Characteristics
    - Health Effects
    - Safety
    - Ecological
    - Land Use and Aesthetics
- Selection of Regulating Parameters
    - Chemical
    - Physical
- Existing and Proposed Regulation
    - Solid Waste Disposal
    - Hazardous Waste Disposal
    - Wastewater Disposal
    - Water Quality Criteria
    - Air Pollution Regulations
- Best Practicable Control Technology Currently Available
    - Guidelines and Limitations
    - Cost
        - Economic and Institutional Energy

b. A potential is present for pollution of groundwater resulting from land disposal of FGD sludges, e.g., ponds and landfills. The assessment of the degree of potential pollution is considered site-specific and complex. Some interdependent factors to be considered in an assessment include the following:

1. The chemical and physical characteristics of the FGD sludge being disposed, these characteristics being a function of the FGD system (e.g., flue gas composition, scrubber water chemistry, and absorbent used), the treatment provided the waste sludge prior to disposal (e.g., dewatering, commercial and noncommercial treatment and stabilization), and time. The physical and chemical characteristics, in turn determine the quality and quantity of leachate generated by the in-place sludge. The leachate contaminants considered to be of interest are TDS, Se, Hg, F, B, Pb, and As. None were reported as exceeding drinking water standards by more than a factor of 10. The chemical speciation of these contaminants was recommended as requiring further investigation.

2. The characteristics of the land disposal site, e.g., soil type, groundwater quality, groundwater hydrology, geology, meteorology, and surface terrain pertinent to flood protection and by-pass of surface waters. These disposal site characteristics are important in determining the fate and impact of the leachate generated by the in-place FGD sludge.

3. The design of the disposal site. This includes the need and type of liner, sludge containment area dimensions (particularly depth), dike construction, sludge handling and circulation of supernatant, prevention of public access, safety precautions, and other design considerations.

4. Since indefinite containment of the waste FGD sludge contaminants was not considered possible, time is a significant parameter. Plastic liners will eventually deteriorate; impervious clays will allow some seepage; and chemically treated sludges may lose their integrity. Therefore, in evaluating land disposal of FGD sludge, the decision is not whether contaminant release will be allowed, but rather the rate of contaminant release that is environmentally acceptable for the present and over the long term.

5. It was recommended that future regulations for land disposal incorporate the factors defined in (1) through (4) above. In order to do so, substantially more interdisciplinary research was considered necessary to provide the data upon which to formulate decisions.

c. Available cost information was considered fragmentary and in some cases difficult to interpret. In order to determine the future economic impact of proposed FGD sludge regulations on industry, additional cost estimates were recommended for FGD management systems encompassing improvements.

d. It was concluded that studies of FGD sludge disposal to date have concentrated heavily on the empirical evaluation of environmental impact and lack any development of theoretical explanations for the observed behavior. The areas of groundwater contamination and contaminant speciation were particularly cited.

Several areas recommended as requiring basic research, generally beyond the scope of existing sludge disposal studies, were identified:

a. A theoretical model that can be used universally to describe the chemistry, physics, and hydraulics of groundwater contamination migration

b. Determination of the environmental cost benefit realized through the use of various sludge disposal options.

Other areas considered as possible extensions of existing disposal research are as follows:

a. Definition of criteria concerning the prevention of catastrophic release of FGD sludge to surface waters

b. Formulation of a thermodynamic model capable of predicting species and concentration of constituents in the liquid and solid phases of FGD sludges

c. Further evaluation of the costs of various FGD sludge disposal options and the associated economic impact of regulating FGD sludge disposal

d. An investigation of the effects of scrubber sludge on handling and disposal equipment

e. An evaluation of the environmental impact of disposal of calcium sulfite waste versus forced oxidation of gypsum prior to disposal

f. More emphasis on the characterization and disposal consequences of double alkali sludges, resulting particularly from the high sodium and ammonium salts concentration.

5.1.8 Environmental Effects and Control of Various FGC Sludge Disposal Options (SCS Engineers)

In this program, which was initiated on September 20, 1976, SCS Engineers will conduct a two-part study. In one portion, it will develop and verify a thermodynamic model capable of predicting species and concentration of constituents in the liquid and solid phases of FGD sludges generated under various conditions. The speciation model is expected to assist in recommending in-process changes to minimize mobilization of undesirable contaminants in the sludge.

The other part, which will be conducted concurrently with the modeling studies, will provide a current updating of the economics associated with the disposal of FGD sludges. The results will be in the form of an economic development document for use in the promulgation of disposal guidelines. Completion is expected in December 1978. The scheduling is designed to take advantage of ongoing economic analyses being conducted by EPA contractors in the FGC Waste and Water Program and other programs.

5.2 PROCESS TECHNOLOGY ASSESSMENT AND NEW TECHNOLOGY DEVELOPMENT

The technology assessment and development efforts, totaling four projects, include (1) field studies of untreated and chemically treated FGC wastes, (2) FGC waste leachate disposal site liner compatibility studies, (3) studies to correlate waste solid characteristics with scrubber operating conditions, and (4) dewatering equipment design studies.

5.2.1 Evaluation of FGD Waste Disposal Options (Louisville Gas and Electric)

Studies of various chemical processes for the treatment of FGC scrubber wastes are being conducted in this 18-month project with Louisville Gas and Electric Company (LG&E), Louisville, Kentucky. Scrubber wastes from the LG&E Paddy's Run No. 6 are being used. Laboratory testing and evaluations of treated wastes are nearly completed. Work was initiated in May 1976. The laboratory test program, all chemical analyses, and program evaluation are being conducted by Combustion Engineering, Windsor, Connecticut. The University of Louisville will perform disposal site tests, field sampling, and physical testing of field samples.

Laboratory-scale tests are being conducted to determine optimum conditions for chemical treatment and physical stabilization of carbide lime and commercial lime FGC scrubber wastes. Scrubber wastes have been treated with carbide lime, slaked lime, and portland cement additives. Some of these formulations contained fly ash.

The field studied will include eight 25 yd^3 (19 m^3) above-ground impoundments of the treated wastes. Leachate, runoff, and physical property tests of stabilized and unstabilized wastes are planned. Eight treated wastes will be selected for evaluation in 100 yd^3 (17 m^3) underdrained disposal ponds. As in the smaller-scale impoundment studies, leachate, runoff, and physical properties of the wastes will be determined.

An interim report is planned upon completion of the laboratory studies, approximately eight months after the start of the program. Field evaluations are scheduled to begin in December 1976 and continue for approximately one year thereafter. A final report will be issued on the conclusion of the program.

5.2.1.1 Laboratory Program

A total of 59 mixtures encompassing a matrix of absorbents, additives, and fly ash conditions were evaluated using the 60-day unconfined compressive strength of the mixes as the primary screening parameter. Permeability tests were also conducted on certain mixtures. The unconfined compressive strength tests were carried out on samples cured for 60 days in a humidity chamber. The permeability determinations were made on samples confined underwater for 30 days. Final selection for field demonstration is being based on the amount of additive required and the permeability. Selected samples of sludge and fly ash mixtures are undergoing four-cycle freeze-thaw tests after a 7 to 8 day curing period. Similar tests are also planned for commercial lime sludge mixtures.

Wastes taken from the thickener underflow (24 percent solids) and treated with carbide lime and lime additives were found to be too soft to measure unconfined compressive strength. All other slurry mixtures, which were filtered to 42, 55, and 65 percent solids and treated, exhibited strengths in the range of 7 to 400 psi, with the major portion of the mixes being above 50 psi (Table 55). Subsequently, nine commercial lime sludges have been added to the test matrix (Table 56).

The permeability criterion established in this project for acceptable landfill material was that it be in the range of 10^{-6} to 10^{-7} cm/sec, a rate similar to that of medium-stiff kaolinite clay. The mixtures selected for permeability measurements and the data obtained thus far are shown in Table 57 and have been in the range of about 3×10^{-6} to 6×10^{-7}, except for the mixtures made with the 24 percent solids (thickener underflow), which were more permeable by a factor of 10. Permeabilities will also be determined for mixtures outlined in Table 56.

TABLE 55. SIXTY-DAY UNCONFINED COMPRESSIVE STRENGTH OF TREATED AND UNTREATED FGD WASTES

Sludge		Additive		Fly Ash to Scrubber Solids Ratio	60-Day Unconfined Compressive Strength, psi
Type	Percent Solids	Type	Amount, %		
Carbide Lime	24	Carbide Lime	5	1:1	Too soft
			25		Too soft
		CaO	5	1:1	Too soft
			20		Too soft
	42	Carbide Lime	5	1:1	57.1
			10		64.1
			15		35.9
		CaO	3	1:1	47.5
			5		62.8
			10		63.0
	55	CaO	5	0:1	29.0
			3	1:1	235.8
			5		176.3
			10		270.2

TABLE 55. SIXTY-DAY UNCONFINED COMPRESSIVE STRENGTH OF TREATED AND UNTREATED FGD WASTES (Continued)

Sludge		Additive		Fly Ash to Scrubber Solids Ratio	60-Day Unconfined Compressive Strength, psi
Type	Percent Solids	Type	Amount %		
Carbide Lime	55	Carbide Lime	0	0:1	Not available
			5		63.9
			0	1:1	101.6
			3		174.6
			5		344.2
			10		382.7
Commercial Lime	50	Portland Cement	3	0.5:1	10.6
			5		10.8
			10		40.9
			3	1:1	37.9
			5		19.3
			10		83.4
			3	1.5:1	46.4
			5		69.5
			10		134.2
		CaO	3	0.5:1	50.6
			5		60.0
			10		63.5

TABLE 55. SIXTY-DAY UNCONFINED COMPRESSIVE STRENGTH OF TREATED AND UNTREATED FGD WASTES (Continued)

Sludge		Additive		Fly Ash to Scrubber Solids Ratio	60-Day Unconfined Compressive Strength, psi
Type	Percent Solids	Type	Amount, %		
Commercial Lime (Continued)	50	CaO (Continued)	3	1:1	59.1
			5		137.5
			10		189.5
			3	1.5:1	86.8
			5		249.0
			10		404.5
		$Ca(OH)_2$	3	0.5:1	49.5
			5		150.8
			10		236.0
			3	1:1	94.9
			5		187.2
			10		392.6
			3	1.5:1	7.1
			5		61.6
			10		48.9
	65	Portland Cement	3	0:1	23.9
			5		27.4

TABLE 55. SIXTY-DAY UNCONFINED COMPRESSIVE STRENGTH OF TREATED AND UNTREATED FGD WASTES (Continued)

Sludge		Additive		Fly Ash to Scrubber Solids Ratio	60-Day Unconfined Compressive Strength, psi
Type	Percent Solids	Type	Amount, %		
Commercial Lime (Continued)	65	Portland Cement (Continued)	3	0. 5:1	31. 0
			5		31. 9
			3	1:1	53. 0
			5		65. 3
		None	0	1:1	21. 0
		CaO	3	0. 5:1	39. 4
			5		91. 0
			10		74. 5
		$Ca(OH)_2$	3	1:1	34. 6
			5		58. 2
			10		54. 7

TABLE 56. ADDITIONAL LABORATORY TEST MIXTURES

Sample Designation	Sludge		Chemical Treatment		Fly Ash to Sludge Ratio
	Type	Solids, %	Type	Amount, %	
P17	Commercial Lime	50	Portland Cement	5	0.5:1
P18		50	Portland Cement	3	1:1
P19		50	Portland Cement	5	1:1
P20		50	CaO	5	0.5:1
P21		50	CaO	3	1:1
P22		50	$Ca(OH)_2$	3	1:1
P23		50	CaO	5	1:1
P24		50	$Ca(OH)_2$	10	0.5:1
P25		50	$Ca(OH)_2$	3	1.5:1

TABLE 57. PERMEABILITY OF TREATED AND UNTREATED WASTES

Sludge		Additive		Fly Ash to Scrubber Solids Ratio	Permeability Coefficient, cm/sec	Mixture Designation
Type	Percent Solids	Type	Percent			
Carbide Lime	24	Carbide Lime	5	1:1	7.6×10^{-5}	P1
			25	1:1	8.5×10^{-5}	P2
	42	Carbide Lime	5	1:1	2.9×10^{-6}	P3
			15	1:1	7.7×10^{-7}	P4
		CaO	5	1:1	1.1×10^{-6}	P5
	55	Carbide Lime	0	1:1	5.7×10^{-7}	P6
			3	1:1	$< 10^{-7}$	P7
			0	0:1	3.9×10^{-6}	P8
			5	0:1	$< 10^{-7}$	P9
Commercial Lime	65	None	0	1:1	7.0×10^{-6}	P10
	50	Portland Cement	3	0.5:1	1.4×10^{-5}	P11
			10	0.5:1	2.9×10^{-6}	P12
			3	1.5:1	2.5×10^{-6}	P13
		CaO	3	0.5:1	4.1×10^{-6}	P14
			10	0.5:1	2.3×10^{-6}	P15
			3	1.5:1	5.7×10^{-7}	P16

Leachate analysis for pH, TDS, Cl^-, $SO_3^=$, Cd, Cu, Pb, Hg, As, $SO_4^=$, Ca, Mg, and Se were performed on the 16 mixtures selected as potential candidates for further impoundment testing.

Table 58 contains the results of leachate analyses obtained from the 16 permeability tests. As a result of the small sample size, the first and second pore volumes were combined, and the fifth and sixth volumes were mixed prior to analysis. In general, trace element concentrations have been reduced considerably between the first and sixth pore volumes collected.

After a preliminary review of the data, it has been reported that the carbide sludge and fly ash samples appear to be more susceptible to the solubilizing of sulfate than the commercial lime mixtures. More information is required from the field tests before definitive conclusions on the selection of optimum mixtures can be made.

Selection of some of the carbide lime sludge mixtures for impoundment evaluation has been made and are identified in Table 59. Two of the mixtures will be evaluated in both large and small impoundments for comparison. The commercial lime sludge mixtures will be selected for demonstration, following completion of leachate tests now under way.

5.2.1.2 Field Disposal Evaluations

Work on the preparation of field disposal sites is being initiated. The location will be at the LG&E Cane Run plant site. Field site evaluation studies are being performed by the University of Louisville.

Eight, small, 25 yd^3 (19 m^3), aboveground impoundments and eight large 100 yd^3 (76 m^3) underdrained disposal ponds are planned.

Chemical analysis of leachate and runoff, as well as physical property testing of the treated wastes, will be performed for all impounded wastes.

5.2.2 FGD Waste Leachate-Liner Compatibility Studies (U.S. Army Engineer WES)

An assessment of the use of liners to contain FGD wastes in disposal ponds is being conducted by the U.S. Army Engineer WES, Vicksburg, Mississippi. An experimental program to determine the compatibility and effectiveness of 18 liner materials with FGD wastes, liquors, and leachates has been defined. Estimates of liner lifetimes are being made on the basis of both a one- and two-year exposure of the liners to the wastes. The economics of FGD disposal by ponding will then be assessed. The cost of the liner materials and placement will be included, as well as associated and construction costs. The program was initiated July 1975 and is scheduled to be conducted over a period of 36 months.

TABLE 58. LEACHATE ANALYSES

Sample[a]	Pore Volume	Conductivity µmho/cm	pH	TDS, ppm[b]	Cl^-, ppm	$SO_3^=$, ppm	Cd, ppm	Cu, ppm	Pb, ppm	Hg, ppm	As, ppm	$SO_4^=$, ppm[c]	Ca, ppm	Mg, ppm	Se, ppm
(I) P1	1&2	3550	11.4	-	115	-	<0.01	0.02	0.1	0.003	-	1580	300	0.05	0.019
	5&6	2350	11.1	-	<5	65[6]	<0.01	0.02	0.1	0.002	0.03	1470	310	0.05	0.006
P2	1&2	8180	12.3	-	180	60[1]	0.02	0.02	0.1	0.008	0.04	1320	540	0.01	0.015
	5&6	7370	12.2	-	< 5	70[6]	0.02	0.02	0.1	0.003	0.01	1530	590	0.01	0.004
(II) P3	1&2	4090	8.4	2500	250	50[1]	0.02	0.06	0.1	0.002	0.05	1860	250	0.10	0.034
	5&6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P4	1&2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5&6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(III) P5	1&2	3750	8.0	2200	155	20[1]	0.02	0.08	0.1	0.001	0.07	1550	230	0.06	0.015
	5&6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(V) P6	1&2	4350	7.9	2600	335	5[1]	0.02	0.06	0.1	0.001	0.05	1940	360	0.14	0.028
	5&6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(VI) P7	1&2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5&6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P8	1&2	6850	7.8	4100	345	30[1]	0.02	0.06	0.2	0.001	0.05	5390	260	940	0.023
	5&6	2500	7.5	1500	<5	-	<0.01	0.02	0.1	0.002	0.01	1960	300	130	0.002
(IV) P9	1&2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5&6	-	-	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 58. LEACHATE ANALYSES (Continued)

Sample[a]	Pore Volume	Conductivity µmho/cm	pH	TDS, ppm[b]	Cl^-, ppm	$SO_3^=$, ppm	Cd, ppm	Cu, ppm	Pb, ppm	Hg, ppm	As, ppm	$SO_4^=$, ppm[c]	Ca, ppm	Mg, ppm	Se, ppm
P10	1&2	2850	7.8	1700	10	40^1	0.02	0.02	0.1	0.018	0.03	1580	320	0.18	-
	5&6	2000	7.7	1200	15	-	<0.01	0.02	0.1	0.001	0.03	1470	300	0.16	0.003
P11	1&2	2450	8.9	1500	10	60^1	0.02	0.04	0.1	0.003	-	1390	250	0.17	0.003
	5&6	550	9.2	300	<5	60^6	<0.01	<0.02	<0.1	0.001	0.02	280	70	0.06	<0.001
P12	1&2	2200	11.6	-	<5	85^1	<0.01	0.04	<0.1	0.002	<0.01	270	11	0.01	-
	5&6	420	9.7	250	<5	105	<0.01	0.02	<0.1	<0.001	<0.01	110	14	0.02	-
P13	1&2	2650	8.0	1600	20	35^1	<0.01	0.02	0.1	0.069	0.02	1550	200	0.21	-
	5&6	620	9.1	370	<5	210	<0.01	<0.02	<0.1	0.001	0.03	260	95	0.12	-
P14	1&2	5650	12.2	-	10	-	0.02	0.02	0.1	0.001	0.01	140	240	0.01	-
	5&6	3850	12.1	-	15	-	<0.01	0.02	0.1	0.002	<0.01	44	160	0.01	-
P15	1&2	6690^2	12.1^2	-	<5	45^2	0.02	0.06	0.1	0.001	<0.01	840	470	0.38	-
	5&6	5400	12.2	-	<5	-	<0.01	0.02	0.1	0.001	<0.01	110	270	0.01	-
P16	1&2	1800	9.3	1100	15	230	<0.01	<0.02	<0.1	0.001	0.01	440	6.7	0.02	-
	5&6	-	-	-	-	-	-	-	-	-	-	-	-	-	-

NOTE: Superscripts denote the pore volume used in the analysis.

[a] Samples are marked on the basis of permeability runs (see Table 57).

Roman numerals refer to mixtures selected for field demonstration (see Table 59). Samples III, IV, and VI have not been sufficiently permeable to allow collection of a leachate sample.

[b] The total of the dissolved solids is an approximate value obtained from the conductivity. This approximation can only be made if the pH is between 5 and 10. Absolute values for TDS cannot be obtained for these samples.

[c] Total sulfur is expressed as $SO_4^=$.

TABLE 59. IDENTIFICATION OF MIXTURES FOR IMPOUNDMENT EVALUATION

Sludge		Additive		Fly Ash to Scrubber Solids Ratio	Impoundment Designation		Permeability Test Designation
Type	Percent Solids	Type	Percent		Small	Large	
Carbide Lime	24	Carbide Lime	5	1:1	I_s	I_1	P1
	42	Carbide Lime	5	1:1	II_s	II_1	P3
	42	CaO	5	1:1	-	III_1	P5
	55	Carbide Lime	5	0:1	IV_s	-	P9
	55	Carbide Lime	3	1:1	-	V_1	P6
	55	Carbide Lime	5	1:1	VI_s	-	P7
Commercial Lime – Mixtures To Be Selected							

A total of 72 test cells approximately 11-13/16 inches inner diameter, containing the 18 liner materials, and contacting a layer of 6 inches of compacted soil has been assembled. A total of four gallons of sludge, forming a column about eight einches high, is used to inundate the liner. Approximately two gallons of water (approximately five inches high) covers the sludge. The test cells are housed in a temperature-controlled environment and are being pressured at a rate of 2 psi per month to simulate a disposal site fill cycle. The pressure will be increased until an equivalent 30-foot sludge depth (20 psi) is reached.

Physical property and durability tests such as weight, thickness, density, and tensile strength have been performed on the as-received membrane liner materials and will be made again in replicate after both a 12- and a 24-month exposure. The leachate from each cell will be measured and analyzed. Daily monitoring of the test cells is being conducted to observe if any breakthroughs occur.

Six sprayon-type materials, 10 additives mixed with soil, and 2 prefabricated membranes are currently under testing (Table 60). The additives have been mixed with clayey silt soil, or silty sand, to form a six-inch thick liner. The liner materials are exposed to FGD wastes from plants burning Eastern coal, one from a lime-scrubbed flue gas and the other limestone (Table 61).

Screening tests for liner permeability were conducted for various liner formulations and materials. The specimens were subjected to a 2-foot head of water. Silty sand and clayey silt soil were combined with various proportions of admix materials and tested. The results are summarized in Table 62. Four admixes (fly ash, cement with fly ash, lime with fly ash, and aniline-furfural) and one sprayon material (SSK) were rejected as unsuitable because of excessive permeability (Table 63). Control tests on the soil permeability were conducted, and the results are reported in Table 64.

Initial data on the average leakage rate of the four test cells for each of the liner materials are shown in Figure 44. Chemical analyses of the leachate are being performed on samples collected from each test cell.

5.2.3 Lime and Limestone Wet Scrubbing Waste Characterization (TVA)

The effects of scrubber operating conditions on FGC waste characteristics are being correlated in this program, which is part of an interagency agreement with TVA, Power Research Staff, Chattanooga, Tennessee. The FGC waste materials from the TVA Shawnee scrubber facility are being characterized and the physical and chemical properties correlated with scrubber operating conditions. Although FGD sludges have received extensive physical and chemical characterization in the past, the total range of variability of the solids and their characteristics as a function

TABLE 60. LINER MATERIALS BEING TESTED

Material	Material Type	Manufacturer
Prefabricated Membranes		
Total Liner	Elasticized polyolefin (30 mil)	The Goodyear Tire and Rubber Co.
T-16	Black neoprene-coated nylon-reinforced fabric	Reeves Brothers, Inc.
Sprayon Type		
DCA-1295	Polyvinyl acetate	Union Carbide
Dynatech Formulation 267	Natural rubber latex	Dynatech Research & Development Co.
Uniroyal	Natural latex	Uniroyal, Inc.
Aerospray 70	Polyvinyl acetate	American Cyanamid
AC 40	Asphalt cement	Globe Asphalt
Sucoat	Molten sulfur	Chevron Chemical Co.
Admixes[a]		
Cement	(10%)[b]	Dundee Cement Co.
Lime	(10%)	Williams Keith Lime Co.
Cement with Lime	(4% Portland Cement, 6% lime)	
M179	Polymer bentonite blend (4%)	Dowell Division of Dow Chemical
Guartec (UF)	A light grey powder (4%)	General Mills
Asphalt Concrete[c]	(11% cement, 1/2-in. aggregate)	Local Contractors
TACSS 020	(6%)	Takenaka Co., Japan, Distributed in U.S. by Air Frame Mfg. Co., Calif.
TACSS 025	(6%)	Takenaka Co., Japan, Distributed in U.S. by Air Frame Mfg. Co., Calif.
TACSS C400	(15%)	Takenaka Co., Japan, Distributed in U.S. by Air Frame Mfg. Co., Calif.
TACSS ST	(15%)	Takenaka Co., Japan, Distributed in U.S. by Air Frame Mfg. Co., Calif.

[a] Soil is clayey silt, except where noted by c.

[b] The number in parentheses indicates the application rate in percentage of test material based on dry soil weight.

[c] Soil is silty sand.

TABLE 61. FGD WASTES

Type of FGD Waste	Designation	Wet Density at 23°C, $\mathrm{lb/ft^3}$	Source of Coal	Sample Source
Lime-scrubbed	A	88.8	Eastern coal	Duquesne Light Co., Phillips Power Station
Limestone-scrubbed	B	83.6	Eastern coal	Commonwealth Edison, Will County Station, Unit No. 1

TABLE 62. EVALUATION OF SPRAYON AND ADMIX TEST MATERIALS

Test Material	Application Rate	Soil Type	Remarks
Sprayon			
DCA-1295	0.75 gsy[a]	Silty sand	Penetrated surface 1/16 in., no leakage.
Aerospray 70	0.75 gsy	Silty sand	Penetrated surface 1/32 in., no leakage.
Dynatech 267	0.75 gsy	Silty sand	Penetrated surface 1/64 in., no leakage.
Uniroyal	0.75 gsy	Silty sand	Penetrated surface 1/64 in., no leakage.
AC 40	0.75 gsy	Silty sand	Penetrated surface 1/64 in., no leakage.
SSk	0.75 gsy	Silty sand	Penetrated surface 1/32 in., slight leakage.
SSk	1.0 gsy	Silty sand	The membrane covering the test specimen ruptured after 5-2/3 days. Prior to this time, the specimen had exhibited slight (49 ml total) leakage.
SSk	0.75 gsy	Silty sand & clayey silt	Ineffective on both soil types after approximately 7 days.

[a] gsy: gallons per sq yd.

TABLE 62. EVALUATION OF SPRAYON AND ADMIX TEST MATERIALS (Continued)

Test Material	Application Rate	Soil Type	Remarks
Admix			
Portland Cement	8%[a]	Silty sand	Each specimen leaked. Judged inadequate as an integral part of a liner system for this soil type.
	10		
	12		
	16		
	20		
	24		
Portland Cement	6%	Clayey silt	No leakage.
	8		Slight leakage.
	10		No leakage.
Cement-Fly Ash	2% cement, 8% fly ash.	Silty sand	Started leaking soon after test began. Judged unacceptable as a linear material under stated conditions.
	5% cement, 5% fly ash.	Silty sand	
	8% cement, 2% fly ash.	Silty sand	
Hydrated Lime	6%	Silty sand	Leaked badly, failed.
	8		
	10		
Lime-Cement	2% lime, 8% cement.	Silty sand	Same as cement-fly ash.
	8% lime, 2% cement.	Silty sand	
	5% lime, 2% cement.	Silty sand	

[a] Percentage based on dry soil weight.

TABLE 62. EVALUATION OF SPRAYON AND ADMIX TEST MATERIALS (Continued)

Test Material	Application Rate[a]	Soil Type	Remarks
Admix (Continued)			
Lime-Fly Ash	2% lime, 8% fly ash.	Silty sand	Same as cement-fly ash.
	5% lime, 5% fly ash.	Silty sand	
	8% lime, 2% fly ash.	Silty sand	
Fly Ash	6, 8, 10%	Silty sand	Same as hydrated lime.
M-179	4% 8 10	Silty sand	None of these specimens leaked, however, the top of each became soft and slimy after the 7-day permeability test. Rejected for use with silty sand soil. Material will be used in a test cell with clayey silt soil.
Guartec UF	4% 8 10 12	Silty sand	Same remarks as for M-179 above.
AM9	10%	Clayey silt	Samples shrank approximately 1/32 in. in the middle of the top portion of each specimen. Both samples were leaking after 67 hr of testing.
	10	Silty sand	Samples very soft, specimens leaked 24 ml (av) after 1 hr 45 min.

[a] Percentage based on dry soil weight.

TABLE 62. EVALUATION OF SPRAYON AND ADMIX TEST MATERIALS (Continued)

Test Material	Application Rate	Soil Type	Remarks
Admix (Continued)			
Aniline-Furfural (2.1% aniline, 1.2% furfural)	3.3%	Silty sand & clayey silt	Both specimens exhibited high compressive strengths and were unaffected by water but were highly permeable. Rejected.
TACSS T-025-NF	6%	Clayey silt	No leakage.
	10	Clayey silt	27 ml/day leakage.
	15	Clayey silt	34 ml/day leakage.
	6%	Silty sand	1/4 ml/day leakage.
	10	Silty sand	7.6 ml/day leakage.
	15	Silty sand	8.5 ml/day leakage.
TACSS T-020-NF	6%	Clayey silt	No leakage.
	10	Clayey silt	No leakage.
	15	Clayey silt	No leakage.
TACSS T-020-NF	6%	Silty sand	No leakage.
	10	Silty sand	No leakage.
	15	Silty sand	One specimen passed, one failed.

TABLE 63. LINER MATERIALS REJECTED

Material[a]	Reason	Replaced in Test Program by
Prefabricated Membranes		
T85	Leakage at joint. Did not pursue study to improve joining methods.	T105
T105	Leakage at joint. Did not pursue study to improve joining methods.	T16
Admixes		
Fly Ash	Excessive permeability	TACSS 020
Cement with Fly Ash	Excessive permeability	TACSS 025
Lime with Fly Ash	Excessive permeability	TACSS C400
Analine, Furfural	Excessive permeability	TACSS ST
Sprayon Type		
SSK	Excessive permeability	SUCOAT

[a] See Table 5.2.2c for mixtures tested.

TABLE 64. PERMEABILITY COEFFICIENTS USING WATER

Conditions	Permeability,[a] cm/sec
6-in. compacted silty sand	81×10^{-6}
6-in. compacted silty sand with lime sludge	49×10^{-6}
6-in. compacted silty sand with limestone sludge	47×10^{-6}
6-in. compacted clayey silt	16×10^{-6}
6-in. compacted clayey silt with lime sludge	7×10^{-6}
6-in. compacted clayey silt with limestone sludge	1×10^{-6}

[a] The liquid was passed through a porous plastic filter at the bottom of the test cell. The permeability of the filter was $28,500 \times 10^{-6}$ cm/sec.

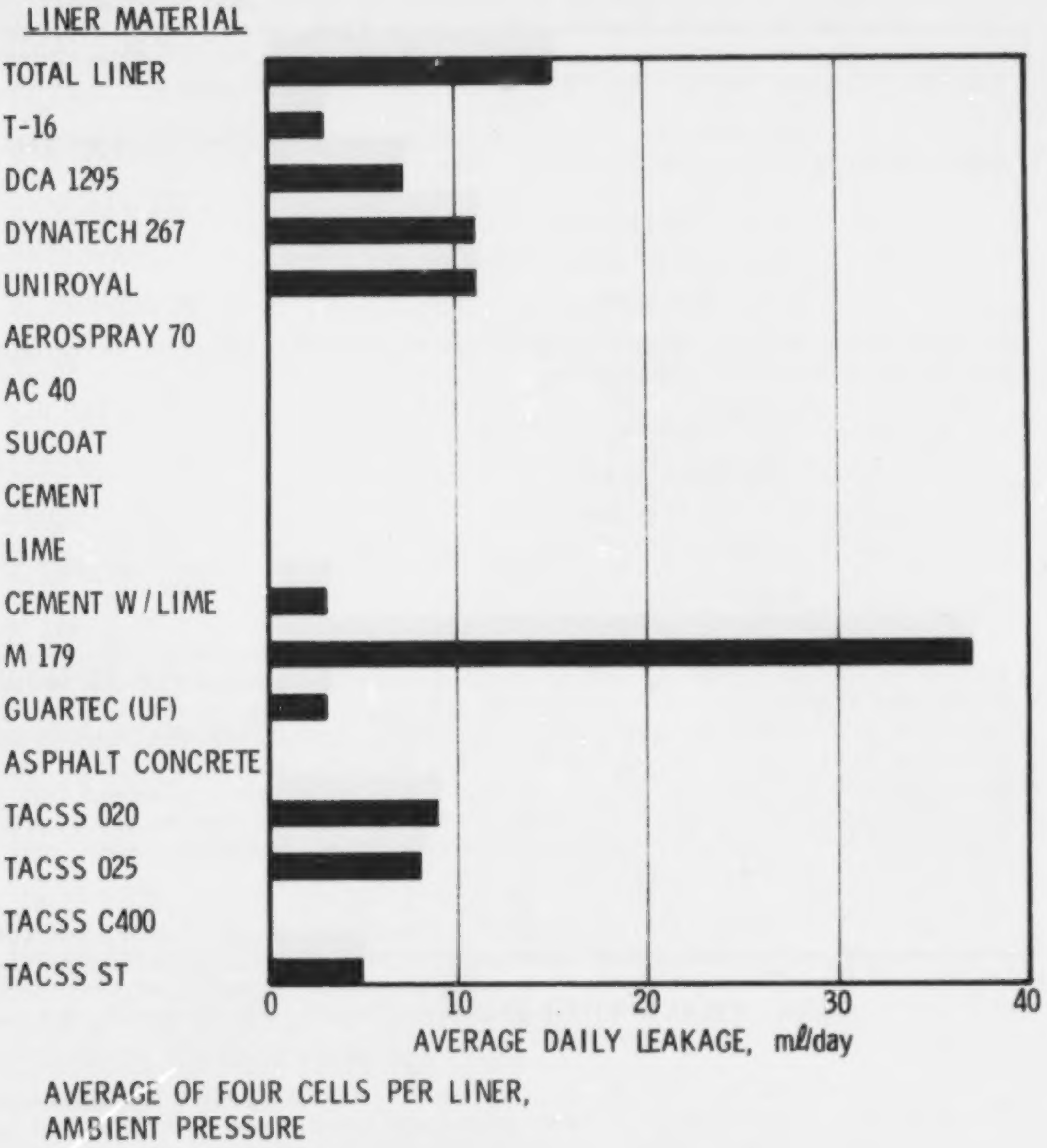


Figure 44. Average leakage rate of liner specimens

of scrubber operation have not been studied. The goal of the program is to determine the feasibility of controlling waste characteristics to improve disposal and utilization economics.

Correlation of the Shawnee scrubber operation and sludge characteristics is scheduled for completion by the middle of calendar year 1977. During the period March 1975 to June 1976, slurry and solids characterization studies were conducted on 84 samples from the Shawnee Test Facility TCA and venturi and spray tower scrubbing systems.

Results are reported from the data obtained from analysis of solids from the following scheduled tests:

a. Mist eliminator testing
b. Magnesium oxide addition
c. Factorial testing

Present plans include examination of solids from the following tests, which are to be conducted in the future:

a. Variable load
b. Maximum oxidation
c. Fly ash free testing
d. Maximum SO_2 removal efficiency
e. Reliability testing

The plant operating conditions that appear to be most closely related to variations in the solids compositions and properties are variable liquid-gas ratios, presence of fly ash, scaling potential of the mother liquor (i.e., degree of $CaSO_4 \cdot 2H_2O$ supersaturation), and the control of oxidation in the solids as indicated by SO_4 for SO_3 isomorphic substitution in the structure of $CaSO_3 \cdot 1/2H_2O$ crystals.[4] The study also gathered data on the conditions during which optimum crystal growth occurs because of the significance of this factor on pond site dewatering, filtration rates, and the liquid entrainment in the solids.

Solids samples obtained from the TCA and venturi and spray tower scrubbing process loops generally consist of calcium sulfite hemihydrate, fly ash, and gypsum, with trace amounts of unreacted absorbent and quartz. The calcium sulfite hemihydrate species is generally the major component (50 to 70 percent) of the solids.

The specific form in which the sulfite species appears was found to be directly related to the type of absorbent used (lime or limestone) and independent of the scrubber configuration (TCA or venturi and spray tower).

When limestone was used as the absorbent, the sulfite crystallized predominantly as well-formed single plates; on the other hand, with lime as the absorbent, the sulfite appeared as spherical, closely interpenetrating aggregates. The average size of the sulfite plates formed from the limestone system appears to be inversely related to the system stoichiometry. No relationship has been seen in the lime system. Besides the sulfite, fly ash is one of the more significant of the accessory components in sludge samples, comprising 20 to 40 percent by weight of the solids composition. The spheres may be solid or hollow and consist of an amorphous alumino-silicate material, sometimes containing calcium and/or iron.

The sedimentation behavior of the scrubbing slurry studies may be described principally as zone settling. Solids morphology was found to exert a strong influence on settling behavior. In samples with large proportions of very small plates, settling is inhibited because more liquor is entrapped upon reaching the compression stage because of a much higher incidence of interparticle contact.

The initial report of these studies, both qualitative and quantitative, have used comparative optical, x-ray, infrared, and SEM investigations of the sludges from the Shawnee scrubbers and provide a good base for describing the range of variability observed in sludge phases. Settling rates and bulk densities provide data on the physical properties of sludges.

At this point in the project, data collection is not complete, and in many cases no firm conclusions can be drawn between data trends and process variables. In some cases, definite relationships have emerged, but these are still subject to further refinement or modification upon completion of the sampling program.

An important factor that is reported to require further evaluation is the response time of the solids for showing change in characteristics. This plays a decisive role in characterization of the solids since they are a function of liquor chemistry and scrubber operation averaged over a preceding period of time and not one specific increment. The time required for the solids as a mass to adjust to a specific change and establish a new equilibrium in terms of chemical composition on morphology can range from one to three days. Because of this, time correlations will be meaningful only if these latter factors are representative of some prior finite period of operation.

5.2.3.1 Characterization Techniques

The initial studies involve a comparative optical, x-ray, infrared and SEM analysis of the sludges from the Shawnee scrubbers. Quantitative and qualitative data will be obtained to evaluate the variability of the sludge phases. Settling rates and bulk densities will also be measured.

Scanning electron microscopy and optical microscopy have been used to provide both qualitative and quantitative information concerning bulk solids composition, as well as the specific morphological form of the various individual components. Infrared spectrophotometry and x-ray powder diffraction measurements have been used for semiquantitative analyses of the dried solids. Specific surface area of the solids was determined as an indication of solids component morphology.

Several techniques were used which reflected any changes in crystal structure caused by the substitution of sulfate or carbonate species into the calcium hemihyrate. Optical microscopy was used to provide the index of refraction of the substituted component, while its specific unit cell parameters, which are sensitive to compositional changes, were obtained from x-ray powder diffractometry. In addition, differential scanning calorimetry (DSC) is being evaluated as an indicator of the ease with which the sulfite component will undergo dehydration. Because the temperature of dehydration should, in general, vary inversely with the degree of substitution of sulfate for sulfite, it is felt that the DSC technique may provide such an indicator.

5.2.3.2 Solids Morphology

Solids from the TCA and venturi and spray tower scrubbing process loops are generally comprised of calcium sulfite hemihydrate and fly ash, with trace quantities of gypsum, unreacted absorbent, and quartz.

The concentration of the calcium sulfite hemihydrate species is generally 50 to 70 percent of the solids. Therefore, a study of its occurrence and morphology was considered important as these factors affect such considerations as sludge filtration, clarification, and disposal. When referring to the calcium sulfite hemihydrate crystalline species it is understood that it may be more appropriately described as $x(CaSO_3)\ y(CaSO_4)\cdot zH_2O$ where x is much greater than y, and z approaches 0.5. The specific form in which the sulfite species appears is directly related to the type of absorbent used, i.e., lime or limestone, and is independent of the scrubber configuration (TCA or venturi-spray tower). The calcium sulfite hemihydrate component of the solids samples occurred in several forms. When limestone was used as the absorbent, the sulfite crystallized predominantly as well-formed single plates with average length-width-thickness dimensions in the ratio of approximately 25:20:1 microns. While within a given sample the crystallite size distribution will range over an order of magnitude, the average size may differ only by a factor of two to three from one sample to another. While the flat plates described above are the major form observed, aggregated forms of the sulfite crystals were also observed. This form was reported to be "not uncommon;" most samples examined from limestone scrubbed operation contained incidences of this rosette form with a few samples exhibiting this form as the predominant sulfite occurrence. The maximum reported dimension was 40 microns.

The characteristic form of the sulfite precipitated from scrubbing liquors where lime is used as the absorbent is generally spherical with closely interpenetrating aggregates found to the almost total exclusion of other forms. Unlike the flat plates occuring during limestone scrubbing, the spherical aggregates averaging approximately 10 microns in diameter do not show a wide variation in size distribution within a given sample, although incompletely developed forms and fragments are often observed.

A series of tests with the venturi and spray tower scrubber demonstrated that the sulfite characteristics were independent of the scrubber operation but dependent on the absorbent. During these tests, the use of limestone as the absorbent was alternated with lime. The results repeatedly show the spherical sulfite aggregate occurrence when lime was used. With limestone, flat plates predominated. While this morphology-absorbent relationship was considered to be clearly established, no explanation for this effect is available at this time.

In a limestone test series in which the chloride ion concentration was much higher than any other condition studied (2.13 percent), the aggregates consisted of smaller more densely interpenetrating plates than were usually observed. The exact cause of this difference has not been determined.

In lime systems, no definite relationship has been found between aggregate size and either chemical composition or physical operating parameters. When limestone is used as the absorbent, however, the average size of the plate crystals formed in this environment appears to be inversely related to system stoichiometry, a steadily decreasing average crystallite size, with increasing Ca:S stoichiometry between 0.98 and 1.63. While no precise mathematical relationship between crystal size and stoichiometry was derived, this observation suggests stoichiometries approaching 1.0 in order to promote faster slurry filtration and clarification.

A previously unreported form of "mixed crystal" was observed, occurring during the period January 1, 1976 to January 10, 1976, in both the TCA and venturi and spray tower systems. In this form, a sulfite rosette is in intimate physical association with a well-developed, although often imperfect, gypsum crystal. The gypsum crystals often show a large number of surface cracks and longitudinal crystal defects. Enlarged views of the areas of contact between the two forms show what appears to be $CaSO_3 \cdot 0.5H_2O$ plate crystals growing from the body of the gypsum prism. Occurence of these mixed crystals was not routinely observed in samples other than those included in the time period cited and in these samples only in minor (less than 5 percent) quantitites. These forms may be related to the gypsum-calcium sulfite hemihydrate solid solutions referred to by Borgwardt (Ref. 17). Comparison of sample chemical composition and scrubber operating data for the period of time during which these samples were taken indicates no excursions from normal values which might be helpful in explaining the appearance of these mixed forms. No explanation for their presence is available at this time.

Fly ash is one of the more significant components of the sludge samples examined to date, comprising 20 to 40 percent by weight of the solids composition. It is normally present in the form of featureless spheres ranging in diameter from a submicron size up to greater than 100 microns. The spheres may be solid or hollow and consist of an amorphous aluminosilicate material, sometimes containing calcium and iron. A portion of the fly ash is magnetic and ranges in quantity from 5 to 60 percent by weight. A small fraction of the fly ash constituent is not spherical but appears to be irregularly shaped, vesicular particles. Rarely, $CaSO_3 \cdot 0.5H_2O$ flat plates will be observed to have been precipitated on the surface of a fly ash sphere.

Gypsum and unreacted absorbent was generally observed in very small quantities (less than 5 percent total). The $CaSO_4 \cdot 2H_2O$ occurred primarily as broken and partially decomposed prisms or as twinned forms Unreacted absorbent was seen as partially or almost completely dissolved irregular forms.

The first observed incidence in the present Shawnee studies of sulfite-blended limestone is indicative of a condition in which undissolved adsorbent particles are covered, in varying degrees, with precipitated crystals of $CaSO_3 \cdot 0.5H_2O$). The sample was taken during the time period in which the venturi scrubbing system was being switched from limestone to lime operation.

5.2.3.3 Slurry Settling Behavior

The settling behavior of slurries has been determined by a static method. The samples (approximately 1 liter in volume) are transferred to 1 liter graduated cylinders (6-cm inside diameter with a depth of 42 cm), mixed thoroughly by stirring and repeated inversion of the cylinders, and then allowed to settle. The height of the solids-liquid interface is tabulated and plotted as a function of time.

Under the conditions in the tests (limiting cylinder diameter, static settling, and 12 to 25 percent solids in slurry), zone settling applies in that there is very little particle size of shape differentiation during settling; i.e., the entire body of solids settles simultaneously by dewatering. There is very little free particle settling; rather, all particles settle together, their combined weight gradually forcing the water contained within the slurry past them to the top of the interface. As the settling slurry approaches compression, dewatering channels may be seen in a cross section through the glass cylinder walls. These channels give the appearance of dendritic or tree-like structures arising from many small channels at a depth of 7 to 8 cm beneath the interface and gradually coalescing into a single channel, which allows the water to escape from the settling solids.

Although the amount of preliminary data is limited, it appears that the lime and limestone slurries may be differentiated by both settling behavior and settling rate. Slurries from the lime scrubbing operation appear to settle and approach compaction smoothly, while those produced in the limestone system show a noticeable and reproducible increase in settling rate immediately before, or upon the onset of, compaction. The mechanism for this behavior has not as yet been defined.

Settling rates and behavior for samples of similar particulate composition are generally dependent on slurry percent soilds, with the thicker slurries settling more slowly. This is illustrated in Figure 45, in which the settling rates for some limestone slurries are shown by a plot of interface position as a function of time. It was observed that thicker (higher percent solids) slurries have lower settling rates and take longer to reach the compression stage.

No general relationship between slurry percent solids and slurry settling rates could be defined because solids morphology also exerts a strong influence. An example of this effect is the behavior of slurries obtained from the TCA system on May 14, 1976 and April 12, 1976 (Figure 46). Although the weight percent solids in both slurries are essentially the same, the sample taken on April 12, 1976 settled more than three times faster and attained, when settled to compaction, an ultimate solids weight percent of 68 percent as compared to 38 percent for the sample taken on May 14, 1976. The micrographs of these solids reveal that while both contained a predominance of single plates, the sample taken on May 14, 1976 consisted of a large proportion of very small plates and plate fragments. These smaller particles inhibit settling and entrap more liquor upon reaching the compression state as a result of a much higher incidence of interparticle touching. This limits the amount of liquor that may flow past them during settling and increases the difficulty with which dewatering can occur.

Because of sample handling and shipping, the static settling tests performed at Muscle Shoals are conducted from 3 to 10 days after the samples are originally taken from the process loop. Settling tests conducted at the Shawnee Test Facility, however, are generally performed within a short time after acquisition. In addition, settling data at Shawnee are generated by the Dorr-Oliver method, which differs from a static test in that the bottom of the test cylinder contains a rake rotated at 1/6 rpm during the settling test. In order to compare data generated by the two methods and to evaluate any effects caused by the delay in testing, comparison of the results obtained by both methods was made. It was concluded that no significant systematic difference was evident in the results between the two procedures within the range of sample percent solids studied and within the context of the types of slurry samples included in the tests.

5.2.3.4 Solids Surface Area

Since the size, shape, and complexity of individual solid particles in the scrubbing slurry may influence or control processes such as chemical reaction speed and filtration or dewatering rates, the solids surface area was determined as a measure of the average particle size and complexity of the slurry solids. The method used is based on a nitrogen desorption method described in Reference 18.

The surface area in meters per gram squared range from 1.6 to 7.6 m^2/g. The average specific area for samples obtained during lime scrubbing is greater than that measured for samples taken from systems employing limestone, i.e., 5.4 for lime and 3.3 for limestone. These data

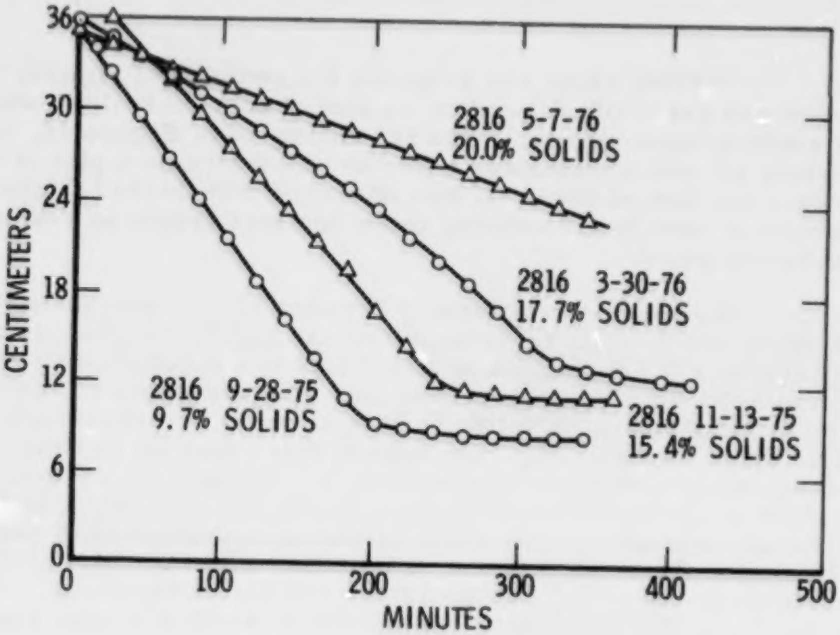


Figure 45. Settling rate: limestone slurry

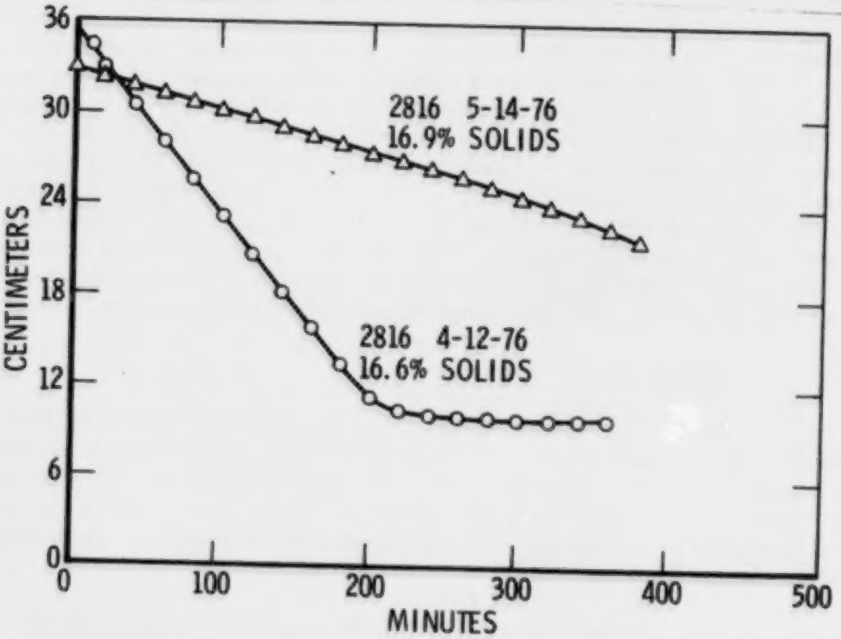


Figure 46. Settling rate: effect of solids morphology

agree with the observation that lime scrubbing tends to precipitate the sulfite crystals as more complex, interpenetrating forms. The values of specific surface area were not readily correlated with variations in sulfite crystal size or complexity (even though this component may comprise, in weight percent, the majority of the sample) because of masking effects of the wide variation in quantity and particle size distribution of the fly ash fraction. Work is in progress to explore possible relationships between the specific area of a sample and its filterability. In addition, a series of "fly ash-free" runs begun on the venturi and spray tower system in June 1976 are expected to provide samples displaying less of the fly ash masking effect and thus simplify further correlational studies.

5.2.3.5 Thermal Analysis of Solids

Thermal analysis of the dried scrubbing solids has been performed, using a Perkin Elmer DSC-2 in the range 330 to 500° C. This temperature range was selected in order to study the thermal dehydration of the $CaSO_3 \cdot 0.5H_2O$ component. It is felt that substitution of carbonate or sulfate into the sulfite structure will result in either a shift of this compound's desolvation temperature away from that of the pure compound or exhibit an increase in complexity of the normally straightforward endothermic desolvation reaction.

Two types of thermal activity were reported. The type of behavior illustrated in Figure 47 has been observed to predominate in samples taken from lime systems. A generally straightforward endothermic desolvation of the sulfite is considered to occur only after an initial reaction, which may represent a gradual desolvation or decomposition of an unknown compound.

A type of thermal activity which is representative of limestone systems is shown in Figure 48. In this case, no initial thermal activity is observed, but the endothermic reaction generally attributed to the sulfite decomposition clearly consists of at least two components, although inadequately resolved. The dashed curve superimposed upon Figure 48 repre-pared $CaSO_3 \cdot 0.5H_2O$.

To date, no correlation has been found between the temperature of reaction as measured and quantities which would measure either SO_4 substitution (infrared spectrophotometric determination of substituted $CaSO_4$) or disturbances in the $CaSO_3 \cdot 0.5H_2O$ structure (the index of refraction or length of crystal axes).

Thermal analysis of lime-limestone scrubbing materials has been reported in Reference 19. In these studies, synthetic sludges were prepared by the addition of fly ash to mixtures of the pure components normally found in such sludges ($CaSO_3 \cdot 0.5H_2O$, $CaSO_4 \cdot 2H_2O$, and $CaCO_3$). These mixtures were studied, subjected to differential thermal analysis (DTA) and thermogravimetric analysis (TGA). The $CaSO_3 \cdot 0.5H_2O$ was found to undergo dehydration in the region 350 to 410° C. This compares

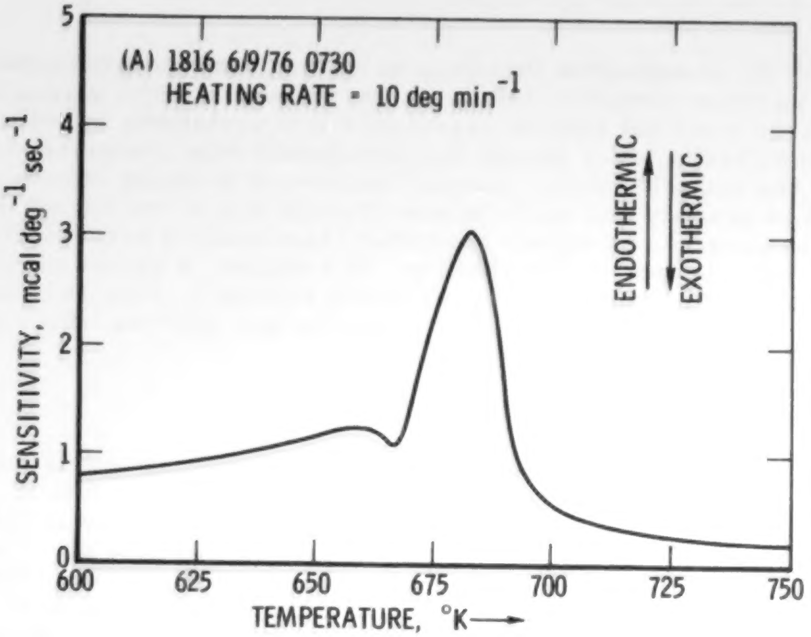


Figure 47. Thermal characteristics: lime system solids

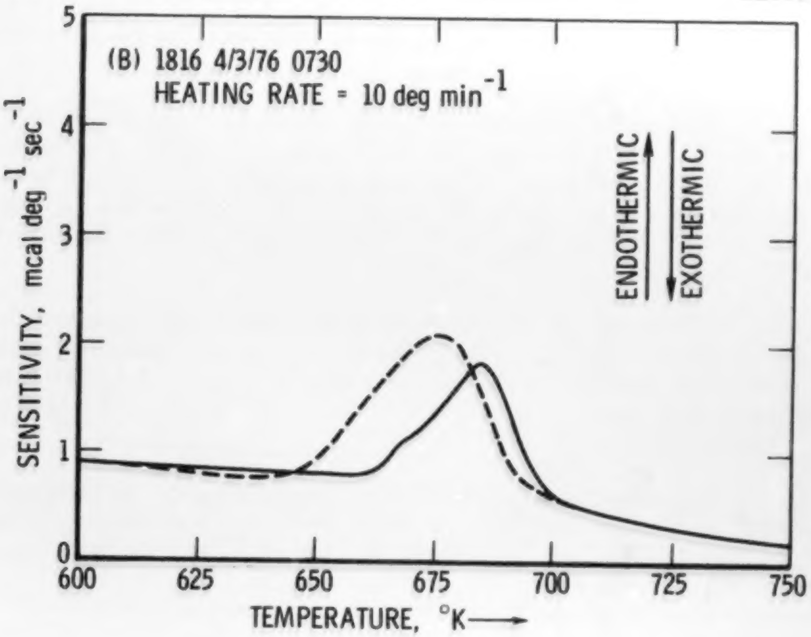


Figure 48. Thermal characteristics: limestone system solids

favorably with the results of this program, which indicate an average decomposition temperature of approximately 390° C. The dehydration temperature of 367° C for the pure compound is reported in Reference 20, which also reports a decomposition temperature of 364° C, utilizing DTA and DSC investigation of the pure compound as prepared in the TVA laboratory. It is not clear which aspects of the complex thermal behavior of the samples examined to date are a result of matrix effects and which may be assigned to reactions of carbonate- or sulfate-substituted $CaSO_3 \cdot 0.5H_2O$ species. Studies in progress are intended to clarify this information.

5.2.3.6 Data Handling and Analysis

A series of computer programs have been written to establish and maintain a slurry sample data base containing all numeric data obtained from this characterization study and selected analytical and operating data supplied by the Shawnee Test Facility. This data base provides machine readable files which are used in ongoing statistical data analysis and report generation and also allows interactive file updating and correction capabilities.

Numerical or statistical analysis to determine relationships between the chemical and physical properties of the scrubbing slurries and solids and scrubber operating parameters has proceeded along several lines:

a. Determination of relationships associated with sludge handling factors, i.e., settling rates, settled bulk densities, ultimate settled percent solids, and operating or chemical parameters such as percent fly ash, average particle size and morphology, absorbent, and hold tank residence time.

b. Relating sulfate substitution as indicated by variations in the index of refraction and length of crystallographic axes to chemical composition, i.e., weight percent sulfate, stoichiometry, saturation ratio, and pH.

c. Evaluating general system operation as functions of absorbent used, make per pass ratio, and liquid to gas ratio.

[illegible] the [illegible] have been indicated, but [illegible] significant factor in masking possible correlations is the [illegible] response time. Assuming an abrupt change in absorbent or additive feed or in scrubber operating conditions, the time required for the solids to adjust to this change and establish a new equilibrium in terms of chemical composition or morphology ranges from one to three [illegible]. The [illegible] is that a [illegible] description [illegible] not be related to the [illegible] taken at that time. Rather, the characteristics of the solids are functions of liquor chemistry and scrubber operation averaged over a preceding period of time. Analyses of these data are continuing, particularly concerning sludge handling properties. Multivariate relationships between variables such as slurry percent fly ash, settling rates, and settled percent solids are currently under investigation.

5.2.4 Dewatering Principles and Equipment Design Studies (Auburn University)

This study was initiated in June 1976 by Auburn University, Auburn, Alabama. Overall objectives include the examination of current dewatering equipment design principles, their applicability to dewatering of FGC wastes, and the potential for developing more promising continuous dewatering methods for increasing the throughput or increasing the solids content of wastes. The economics of the dewatering processes developed will be considered and included in an overall assessment of their feasibility. The initial emphasis is on the application of gravity sedimentation to rapid and inexpensive dewatering of FGC wastes.

Specific tasks include the following:

a. Develop methods for characterizing the physical properties and behavior of FGC wastes. The characteristic indicator is used to provide a basis for selection of type of gravity sedimentation unit; i.e., continuous or semicontinuous and lamella or conventional, for determining design specifications and for directing operations to achieve maximum dewatering efficiency for any given application.

b. Develop procedures based on existing gravity settling mathematical modes, with modifications and extensions, to allow accurate design and analysis of gravity sedimentation units used in treating FGC wastes.

c. Perform bench-scale and pilot tests to evaluate the feasibility of using gravity sedimentation units for treating FGC wastes. The effects of system variables such as location of feed port, design of the feeder head, depth of sludge bed, and solids throughput rate on dewatering efficiency are to be evaluated. Gravity sedimentation methods that can best be utilized in treating FGC wastes will then be recommended.

d. Conduct experiments to determine the best design for the application of channel promoters. Bench-scale and continuous pilot tests are to be performed to evaluate the feasibility of such devices for improving dewatering efficiency while treating FGC wastes.

e. Study the filterability of different types of FGC sludges having been dewatered previously to different levels. Also assess the pumping requirements for the different sludges.

5.2.4.1 Initial Results

A study of those separation processes, particularly sedimentation (thickening) and filtration, currently accepted as offering the best means for dewatering FGC wastes has been emphasized early in the program. The material being used in these studies is carbide lime sludge from LG&E. Progress made in the sedimentation and filtration studies is summarized in the following paragraphs.

5.2.4.1.1 Sedimentation Studies

It was reported that stirring had a pronounced effect on the settling rate in settling column tests. For example, after about a month of settling, slurry that had been stirred only once had a mean solids concentration of 20.7 percent by weight; whereas unstirred slurry had a mean solids concentration of 37.7 percent. These early results indicate that much of the data from past developmental studies at Auburn using phosphatic slimes may be directly applicable in dewatering studies using FGC wastes.

Batch settling tests of the FGC waste included monitoring of solids concentration at a specific height above the settling bottom as well as the height of the solid-liquid interface. These results are being compared to existing dewatering theories to describe the dewatering mechanism and characterize settling behavior. Tests were conducted in columns 8 feet high and 1 foot in diameter, with a 4 feet by 4 inch inner diameter.

5.2.4.1.2 Continuous Settling Studies

Studies to determine the effect of the solids throughput rate on underflow concentration for a base set of operational conditions were initiated. These are expected to provide a baseline for comparison in evaluating the effect of different operational parameters such as sludge blanket height and feed port location on dewatering efficiency.

A significant observation was made while setting up the pilot thickener unit which may result in significantly higher dewatering efficiencies, as well as better control of the pilot thickener. It was reported that parametric pumping had a pronounced effect on underflow concentration while thickening phosphatic slime. The slime was used to simulate the FGC waste and has settling characteristics similar to those of carbide lime wastes. During the test, while holding all operational parameters constant and simultaneously pulsing the slurry feed and underflow flow rates by alternately operating and stopping the pump, underflow concentration increased by 25 percent above that obtained during continuous pumping.

5.2.4.1.3 Economics

Based on previous experience, it was reported that a series of thickeners rather than a single thickener should require the least overall capital expenditure for a given dewatering load. On the other hand, pumping costs are higher when multiple thickeners are used. For computation of the economically optimal number of thickeners, a computer program was designed which relates the economic cost relationships and the baseline solids throughput rate versus underflow concentration curve that will be established (experimentally).

5.3 PROCESS ECONOMICS STUDIES

Economic studies are interwoven within most of the various projects. Assessment of process technology or environmental impact generally includes an examination of the economics involved. However, those primarily related to economics are discussed in this section and include (1) conceptual design and cost studies for current disposal practices and (2) gypsum by-product marketing studies. Both are being conducted by TVA.

5.3.1 Conceptual Design and Cost Studies of Alternative Methods for Lime and Limestone Scrubbing Waste Disposal (TVA)

In this study the TVA Office of Agricultural and Chemical Development, Muscle Shoals, Alabama, is conducting a detailed economic evaluation of several FGC waste treatment and disposal methods.

In addition to the economics of disposal of an untreated waste, the Chemfix, Dravo, and IUCS chemical treatment processes are being examined. These studies are expected to augment those in Reference 5 by providing more detail costs including the effects of major system variables and options and the sensitivity to operating conditions for lime and limestone-based scrubber wastes. Disposal site characteristics, i.e., location, ponding (with and without liners), and landfill will also be included.

Flowsheets, material balances, equipment and material lists, layouts and equipment costs, as well as capital investment and revenue requirements for the 108 cases of four major disposal alternatives, will be included in a detailed interim report that is expected early in the second quarter of calendar year 1977.

Currently, the capital costs for all the processes and options have been defined. The annual operating and lifetime costs will be completed early in 1977.

A Phase II to this study has been defined, which will evaluate the economics of (1) forced oxidation of sulfite wastes to gypsum and (2) the blending of dry fly ash with sludge. This study along with the final report covering both phases is scheduled for completion in the fall of 1977.

5.3.2 Gypsum By-Product Marketing Studies (TVA)

This project is a task to identify the technology, economics, and market potential for by-product gypsum-producing FGD alternatives. It is being conducted by TVA, Office of Agricultural and Chemical Development, Muscle Shoals, Alabama, through an interagency agreement with EPA.

The current study evolved from a preliminary gypsum study conducted for EPA by TVA during early 1974 (Ref. 21), followed by a series of detailed market studies on by-product sulfuric acid and elemental sulfur in the United States (Ref. 22). The gypsum study indicated that production and sale of abatement (by-product) gypsum to the wallboard industry in the United States might offer economic advantages over other waste-producing alternatives.

Included within the current study, are the design and economics for the Chiyoda, Dowa, and Kureha commercial gypsum processes. In addition, a limestone slurry scrubbing process utilizing subsequent oxidation to gypsum is evaluated. Flow diagrams, material balances, and investment and revenue requirement projections corresponding to a 1978 startup are included for each of these processes.

The study includes a survey of the gypsum industry, quality standards for gypsum, and market statistics. In addition, a comprehensive assessment will be made for marketing the SO_2 abatement gypsum for wallboard and cement manufacturing applications in the United States. The most likely candidate power plants will be defined, and expected transportation costs and possible net sales revenue will be projected for the selected plants on the basis of 1978 total demand estimates as well as prorating on the basis of various market applications.

Completion of the study is estimated by the end of the first quarter of the calendar year 1977 at which time a draft report will be avail-available.

5.4 ALTERNATIVE FGC WASTE DISPOSAL METHODS

The intent of work in this area is to assess the potential and the environmental impacts associated with disposal of FGC wastes in mines and in shallow and deep ocean sites.

5.4.1 Evaluation of Alternative FGC Waste Disposal Sites (A. D. Little)

An evaluation of mines and the ocean as FGC waste disposal alternative sites to ponding and landfilling are being evaluated in this program being conducted by A. D. Little, Inc., Cambridge, Massachusetts. Phase I, which included an initial assessment of the technical, environmental, regulatory potential and economic aspects of the disposal of untreated and chemically treated FGC wastes in deep and surface mines and in the ocean, has been completed. The state of the art on technology related to disposal operations on detection, monitoring, and control was reviewed as well as the possible benefits resulting from FGC sludge disposal operations, e.g., mine subsidence control and use as a tailings amendment.

Federal regulations applicable to such disposal have been identified and assessed as to their adequacy in protecting the environment. An assessment of state regulations was made for Pennsylvania inasmuch as it is confronted with the potential of disposing of large quantities of waste, and its mining regulations were considered as representative of those of other states. Based on technical feasibility within regulatory constraints, a number of approaches for implementing ocean or mine disposal systems were identified.

Phase I focused on environmental effects and operational safety as the primary considerations; in Phase II, an assessment will be made of the costs of promising disposal systems including conceptual designs. In Phase II, recommendations will also include plans for subscale pilot demonstrations of such a size that design data for full-scale operations can be obtained.

Phase I was completed in September 1976. Phase II is currently under way and will continue through March 1977. A Phase I report is currently in publication (Ref. 23).

5.4.1.1 Phase I Results

Assessment of the impacts of the waste disposal in mines and the ocean was conducted. Table 65 presents a general outline of the various tasks. Significant project tasks were to evaluate the applicability for mine and ocean disposal and to collect existing data on the physical and chemical properties of both untreated and treated FGC waste by location, process type, and potential quantity produced. Sources were primarily from the U.S. Army WES and The Aerospace Corporation work. It was found that certain data on the properties of FGC wastes which were essential to disposal in the marine and mine environment had not been determined, and a limited experimental program to obtain these data was defined.

5.4.1.1.1 Mine Disposal

The impact assessment with regard to overall technical feasibility was based upon a broad grouping of mines according to the mineral mined, mine capacity, and method of mining, together with ranges of sludge characteristics appropriate for each region of the country. While this assessment yielded general conclusions regarding overall viability of disposal options, any proposed disposal operation must be evaluated on a case-by-case basis, considering the site-specific conditions and the characteristics of the sludge. The type of mines considered on the basis of geographic regions were as follows:

a. Surface area coal mines

b. Underground coal mines

    1. Room and pillar mines

    2. Longwall mines

TABLE 65. STUDY OUTLINE

- Sludge Characterization
  - Chemical Properties of Untreated Sludge
  - Physical and Engineering Properties of Untreated Sludge
  - Effects of Treatment on Sludge Properties
- Mine Disposal
  - Screening of Alternatives
  - Regulatory Environment
  - Environmental Assessment
  - Technology Assessment
  - Disposal Criteria
- Ocean Disposal
  - Environmental Assessment
  - Technology Assessment
  - Disposal Criteria
- Economics of Conceptual Disposal Systems
  - Coal Mine Disposal
  - Ocean Disposal

c. Underground mineral mines

   1. Lead-zinc mines

   2. Limestone mines

Salt mines were not specifically addressed within the scope of the FGC waste disposal study because these mines have been assigned to a higher priority use.

Active, Interior region surface, strip coal mines, active Interior and Eastern room and pillar underground coal mines were determined to be the most promising types for disposal of untreated and treated FGD sludges, for a number of reasons, including their accessibility and availability of space for disposal of the sludge. Such factors as location, mining methods, disposal transport and placement methods, and mine capacity were evaluated in light of geology, water resources, water quality, and biota. Underground limestone and lead-zinc mines were also considered technically suitable, but capacity and location were factors that tended to reduce their attractiveness. Numerous weighting factors were applied, and for these the reader is referred to in Reference 23.

Following are some general considerations relative to coal mine disposal and sludge treatment. Disposal of untreated FGD wastes in surface mines may be acceptable. In some cases, impacts may be reduced by placement of overburden in the mined out area prior to waste placement and if sufficient dilution occurs to the leachate prior to entering, or in mixing with the receiving waters.

Although highly promising, use of underground room and pillar mines for sludge disposal must be decided according to site-specific hydrogeology. Because the mine environment is rock and nonaikaline, attenuation of soluble chemical species is not expected.

In general, data on the effects of sludge treatment on the concentrations of contaminants, particularly trace elements, in leachate are not very definitive. However, certain types of sludge treatment solidify the sludge into a matrix of low permeability. Leachate impacts may be minimized to an insignificant level if an appropriate chemical treatment were employed, simply as a result of reduced permeability.

The use of untreated FGD sludge mixed with mine tailings as an amendment for plant growth was judged to be of minimum benefit. It was determined to be considerably less promising than either limestone or sewage sludge, which are now used. In underground mines, FGD sludge placement would result in the potential of lessening acid drainage formation and long-term subsidence, primarily by sealing exposed coal against air exposure, which leads to pyritic sulfur oxidation and also leads to pillar deterioration.

Recent regulatory attitudes indicate a growing concern for groundwater protection from seepage or leachate from the disposal of wastes. Given the recent Resource Conservation and Recovery Act (RCRA) of 1976, coverage by existing legislation is considered adequate in coverage to encompass all aspects of FGD waste disposal. However, because of the technical difficulties of completely characterizing an underground environment and of locating monitoring wells, it was concluded that regulation must rely on guidelines for site selection and waste acceptance and must allow for case-by-case assessment by professional geologists and geochemists.

Specific conclusions relative to regulatory considerations were reported as follows:

a. The lead authorities for FGD sludge disposal appear to be the federal and state environmental protection agencies.

b. The lead legislation is expected to be the RCRA of 1976. The new RCRA provides for comprehensive regulatory authority in the area of solid and hazardous waste management at the federal level and an institutional framework for planning and regulatory implementation at the state level. The RCRA is expected to be the lead legislation to regulate FGD sludge disposal. In the area of water, both the Federal Water Pollution Control Act (FWPCA) and the Safe Drinking Water Act provide authority to regulate underground discharges. Existing laws and regulations appear to adequately cover transportation of desulfurization wastes as transportation of similar materials by modes of transport under consideration is a frequent and familiar practice of commerce.

c. The combination of federal and state legislation is legally adequate to protect the environment during and after FGD sludge disposal; however, regulations are needed with site selection and waste acceptance guidelines based upon the characteristics of FGD sludge and research on potential environmental impacts.

d. Additional legislation and standards may be required to protect worker health and safety. Administration of the health and safety requirements needs clarification, especially between authorities of the Office of Safety and Health Administration (OSHA) and MESA.

e. Because of the nonpoint source nature of air and water emissions from FGD sludge disposal and the large variations in FGD sludge character, disposal must be regulated on a case-by-case basis.

At the state level, there are laws and regulations which either enhance the federal laws and regulations or fill gaps in the regulations. Laws governing mining activities (i.e., reclamation, sealing, subsidence control, and acid mine drainage) and permit regulations for wastewater effluent, mine drainage, and solid waste disposal sites are covered at the state level.

In assessing state regulations, Pennsylvania was selected as a model state. Pennsylvania is an industrialized state with extensive mining operations and a number of utilities planning or operating FGD systems. The Department of Environmental Resources (DER) currently has lead responsibility for regulating sludge disposal in mines. The regulating statutes do not specifically address FGD disposal in mines; however, collectively, the statutes can be interpreted as providing coverage for all aspects of sludge disposal.

The DER is considering regulatory amendments to existing statutes in order to ensure orderly and environmentally sound disposal of FGD sludge. Some factors regarding mine disposal may be clarified by a pilot field program recently undertaken by DER under an EPA grant to evaluate sludge disposal in underground mines.

Recommendations for additional research or information related to FGD sludge disposal in mines included the following:

a. Additional and more detailed leachate and elutriate data for both treated and untreated sludges including TOS levels in both aerobic and anaerobic environments.

b. Development of more definitive data on engineering properties of untreated sludges and comparison of results with field data. Specifically, Atterberg Limits Test (liquid and plastic), consolidation tests, and triaxial compression tests for a representative range of sludges are needed to determine the ultimate fate (e.g., stability, flow potential, and load capacity) of sludge in various underground and surface mine disposal scenarios.

c. Effects of climate such as freeze-thaw and rewetting of sludge on its physical and handling properties and on pollutant mobility.

d. Potential for corrosion of bulkheads (concrete and steel) by sludge.

e. Potential for SO_2 evolution in disposing of sludge in underground mines containing acidic waters.

f. Laboratory or field tests of hydraulic and pneumatic stowing of various sludges to determine handling properties and define appropriate mine disposal methods.

g. Survey of dust, noise, airborne contaminant, and other health and safety criteria which disposal must meet and an evaluation of the levels of dust created during sludge handling and placement, particularly during intermediate storage and in pneumatic and hydraulic stowing in underground mines.

h. Clarification of roles of OSHA and MESA and other health and safety authorities.

i. Field survey of various mines (coal, limestone, salt, and lead-zinc) to characterize the alkalinity and acidity of drainage, the extent of pillar robbing, the pathways and rate of groundwater flow, and the potential for long-term subsidence.

5.4.1.1.2 Ocean Disposal

Both deep ocean and Continental Shelf disposal alternatives were evaluated and included sludge of three different consistencies, i.e., dewatered (untreated), slurry (dispersed), and brick-like (treated). Numerous environmental and technical factors were considered in the evaluation and are listed in Table 66. Considering these alternatives, two promising options were selected for developing conceptual system designs and associated capital and operating costs, viz., the disposal of untreated FGD sludge in the deep ocean and treated rock-like sludge on the Continental Shelf.

Several general conclusions emerged from the study. First, the need exists for case-by-case analysis of the environmental feasibility of ocean disposal of specific FGD sludges with emphasis being focused on the type of sludge and disposal site environmental conditions. Secondly, all control and monitoring options evaluated appear to be technically feasible. Economic feasibility was considered less definitive and could serve to limit the viability of several of the most promising environmental options.

Specific conclusions included the following:

a. The disposal of untreated or treated, soil-like FGD sludges by bottom dump barge or outfall on the Continental Shelf is considered environmentally unacceptable.

b. According to available information on sulfite toxicity, sulfites require an immediate dilution factor greater than 10,000:1 in the dispersed disposal of untreated sulfite-rich sludges. Technology is not currently available for attaining such dilution factors for sulfite-rich sludges in an economical manner. Therefore, the dispersed disposal of untreated sulfite-rich sludges both on and off the Continental Shelf was currently not considered to be a promising option. Further information on organism uptake and toxicity of TOS may result in a reevaluation of this conclusion.

TABLE 66. FACTORS CONSIDERED IN OCEAN DISPOSAL EVALUATION

- Environmental Assessment
  - Regulatory Environment
  - Fate and Effects of Ocean Disposal
    - Physical Transport
    - Environmental Impact Potential
      - Benthic Sedimentation
      - Sludge Suspended in the Water Column
      - Sulfite-Rich Sludge
      - Trace Contaminants
  - Environmental Impact of Applicable Control Option
    - Restrictions on Sludge Composition
    - Disposal by Dispersion
    - Concentrated Bottom Disposal
    - Chemical Treatment
    - Deep Ocean Dumping

- Technology Assessment
  - Transportation
  - Navigation and Surveillance
  - Monitoring

With the exception of concentrated disposal of brick-like treated material, chemical treatment appears to offer few, if any, advantages over the traditional bottom dump of untreated FGD sludge. The sulfite impacts may be mitigated by chemical treatment, but effects of benthic sedimentation and suspended sludge in the water column would be comparable to those of untreated material.

Disposal options that appear promising and were recommended for further research are as follows:

a. Dispersed disposal of untreated sulfate-rich FGD sludges on the Continental Shelf

b. Concentrated disposal of treated, brick-like FGD sludge on the Continental Shelf

c. Dispersed disposal of untreated sulfate-rich FGD sludges in the deep ocean

d. Concentrated disposal of both untreated sulfate-rich FGD sludge and treated FGD sludges in the deep ocean

In considering regulatory factors coupled with the vigilance in agency attitudes towards ocean dumping, the existing regulations were reported as adequate in ensuring protection of the ocean environment. However, several specific recommendations were made:

a. Pending revisions should be adopted to the existing ocean dumping regulations that would allow for additional empirical considerations in the determination of limiting permissible concentrations.

b. Existing absolute limits on permissible concentrations of mercury and cadmium in solid fractions of wastes should be reevaluated through consideration of the actual anticipated long-term availability of the contaminants on a case-by-case basis.

c. Inherent disincentives to deep ocean dumping, e.g., extra monitoring requirements should be reevaluated in light of the apparent desirability of certain deep ocean disposal options.

No additional sludge-related legislation concerning ocean disposal was considered necessary for the present.

The following research needs were identified as being most important at this time:

a. Development of a body of empirical data concerning dissolution rates of various types of treated and untreated FGD sludges in the representative types of seawater that would characterize the disposal area environs.

b. Empirical determination of the uptake of both liquid and solid constituents of FGD sludges by various marine organisms. In particular, values for uptake associated with short-term exposure of pelagic organisms require investigation.

c. Determination of lethal and sublethal effects thresholds, a variety of representative marine organisms upon exposure to FGD sludges. One of the focal points of such research should be the dynamics of food web transfer of potential toxicants.

5.4.1.1.3 Economics of Conceptual Disposal System Designs

Basis

Conceptual system designs and general capital and operating costs were provided for five ocean disposal and six mine disposal options. As a basis, a 500-MW power plant burning typical Eastern coal (3.0 percent S, 10.0 percent ash, and 0.85 lb of coal/kWh) was assumed producing 365,000 tons per year of dry sludge (including ash). The sludge (with ash) was considered to be available either as a dry filter cake (50 percent solids), a 35 percent solids slurry (thickener underflow), or as treated sludge. No estimates were included for sludge processing such as filtration, drying, fly ash addition, or treatment. However, in cases where treated sludge required handling, estimates for excavation of treated sludge from stabilization ponds were included. Capital costs were based on 1978 completion of construction and included installed equipment cost for the battery limits disposal system (transfer, handling, and placement) engineering and contractors' fees, working capital, owners' expense, startup, and interest and escalation during construction. Capital investment and operating costs did not include sludge processing equipment, site preparation, land cost, auxiliary utilities, or fees for permits. Operating costs include capital charges at 17 percent of total installed cost.

Coal Mine Disposal

Conceptual systems and costs included the disposal of both filter cake (admixed with ash) and treated sludge in onsite and offsite surface area coal mines and the disposal of slurried, untreated sludge (with ash) in onsite underground coal mines. For onsite mines, either truck transport of filter cake and treated sludge or pipeline transport of thickener underflow were used in transport of the sludge. For offsite mines, rail haul of either treated sludge or filter cake was assumed. Preliminary estimates indicated truck haul and slurry pipeline to be impractical for long-distance sludge transport.

For untreated sludge, disposal costs including transfer and intermediate storage ranged from \$3.00 to \$3.50 per dry ton for onsite disposal to \$6.50 to \$8.00 per ton for offsite disposal. Disposal of treated sludge in surface area mines increased costs approximately \$2.00 to \$2.50 per ton to account for excavation of stabilization ponds. The estimates did

not include [illegible]
hydrol[illegible]
For deter[illegible]
as appropriate [illegible]

Ocean Disposal

Conceptual system designs and costs were developed for five ocean disposal options, two for dumping on the Continental Shelf (25 nmi) and three for off the shelf (100 nmi) dumping. Estimates included disposal of both untreated and treated sludge on the shelf and untreated filter cake or thickener underflow and treated sludge off the shelf. While disposal of untreated sludge on the Continental Shelf was not presently considered promising because of the potentially adverse environmental impacts, it was included for comparative purposes.

In preparing the conceptual system designs, it was assumed that the sludge was produced in an Eastern power plant with ready access to the ocean; i.e., facilities for berthing barges were available with sufficient area for installation of a sludge transfer and storage system. Costs were developed for operations including tug and barge combinations and self-propelled ships. In all cases, the system costs utilizing self-propelled ships were found to be less than for a tug-barge combination because of the lower capital investment resulting from shorter cycle times for ships, therefore requiring fewer ships.

Disposal of untreated filter cake (with ash) on the shelf was estimated as $4.00 to [illegible] per [illegible] sludge, with annual costs of about [illegible] ponds for treated sludges. [illegible] treated sludge increased costs [illegible] (on-shelf) ocean disposal. Disposal of thickener underflow in the deep ocean was estimated to cost approximately $1.00 more per ton than filter cake disposal. As with mine disposal costs, these estimates did not include monitoring costs or sludge treatment costs.

5.4.1.2 Phase II Study

stud[illegible]

Based [illegible]
simulat[illegible]

In the Phase II characterization tests, tests to determine chemical, physical, and mechanical properties are being performed to augment and confirm existing data unique to the disposal and fate of the sludge constituents in mine and ocean environments. Laboratory tests (Figure 49) are being performed at A. D. Little, Inc., and at the New England Aquarium (NEA) for ocean disposal to clarify impact issues identified during the Phase I impact assessment. These data will be used as a basis for selecting sludges for Phase III simulation and demonstration testing. Concurrently, sampling, analytical, and test procedures being developed or in use for determining physical and chemical characteristics of sludges will be evaluated. Their applicability to Phase III testing will be determined, and modifications will be defined as appropriate.

Based on the results of the Phase II tests and the evaluation of impact issues identified during Phase I, refinements and adjustments will be made to the Phase I environmental and technical assessments. An update of the regulatory issues are planned as well as a review of control options and disposal criteria.

Preliminary engineering designs will be prepared for at least two mine and ocean disposal options, and the handling, storage, and physical processing required; all transport and intermodal transfer of the sludge; and sludge placement and environmental impact control measures including site monitoring will be considered. Estimates will also be provided for the capital and operating costs for these disposal designs. As a part of the cost and design efforts, cost tradeoffs and cost sensitive areas will be identified.

5.4.1.2.1 Project Status

Samples of eight different types of wastes have been selected on which will be conducted characterization tests appropriate to the waste type and disposal method. These include double alkali filter cake, with and without fly ash (high sulfur coal); centrifuged direct lime scrubber sludge with ash (low sulfur coal); centrifuged gypsum sludge without ash; and direct lime-scrubbing filter cake without ash (high and low sulfur coal). The chemical analyses of these sludges is summarized in Table 67. Recently, sulfate-rich lime and sulfite-rich limestone wastes have been included.

The material balance accountabilities for all samples ranged between 93 and 100 percent, on the assumption that the major phases are $CaSO_3 \cdot 1/2\,H_2O$, $CaSO_4 \cdot 2\,H_2O$, $CaCO_3$, $MgCO_3$, and Na_2SO_4. The values reported for acid insolubles may be somewhat low if some of the iron compounds in the fly ash were leached.

The analytical methods for chemical and physical characterization of FGD sludges used by other investigators are being evaluated. The assessment involves a review in the following areas:

a. Chemical analysis procedures for major and trace constituents

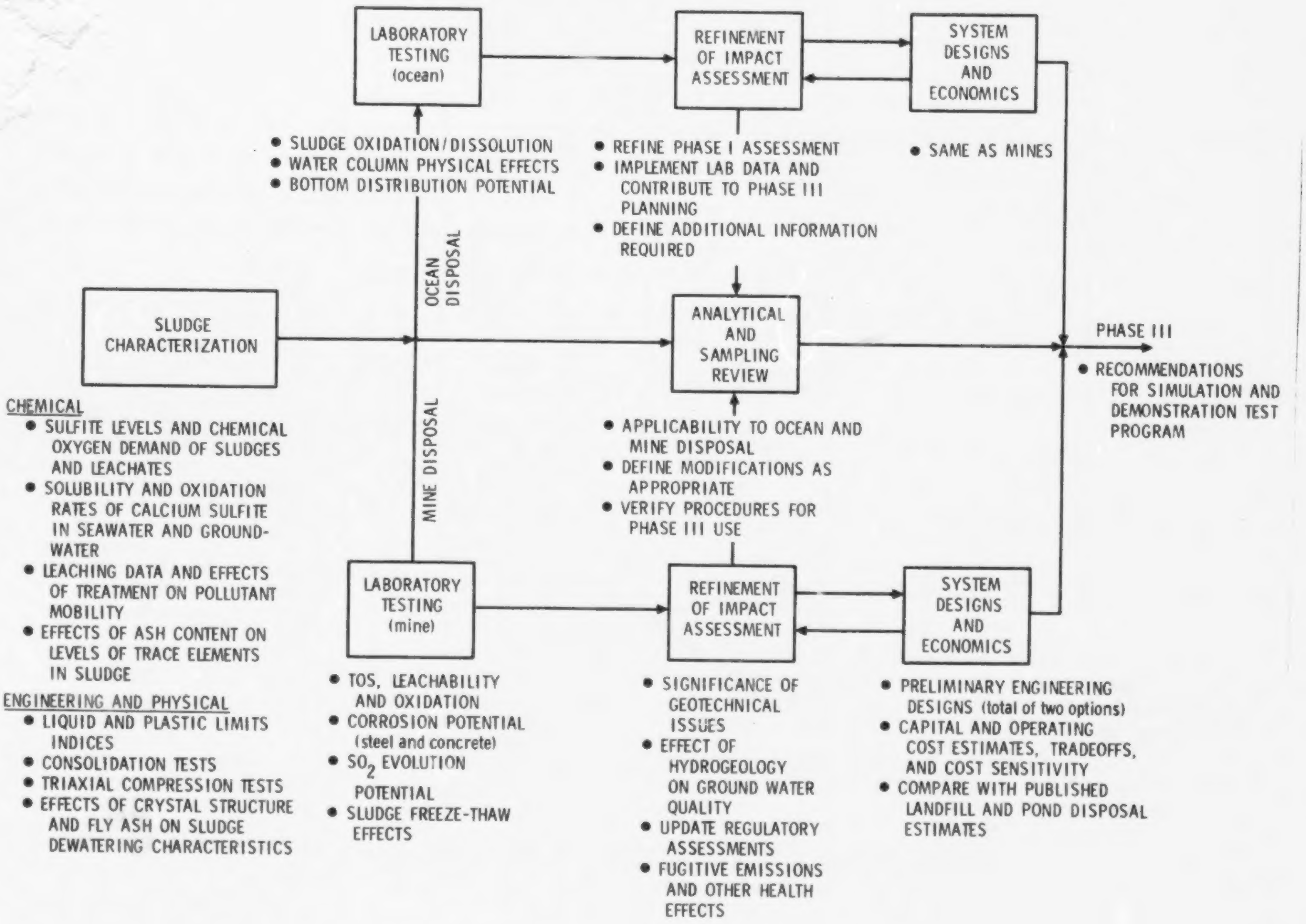

LABORATORY TESTING (ocean)
REFINEMENT OF IMPACT ASSESSMENT
SYSTEM DESIGNS AND ECONOMICS
• SLUDGE OXIDATION/DISSOLUTION
• WATER COLUMN PHYSICAL EFFECTS
• BOTTOM DISTRIBUTION POTENTIAL
• REFINE PHASE I ASSESSMENT
• IMPLEMENT LAB DATA AND CONTRIBUTE TO PHASE III PLANNING
• DEFINE ADDITIONAL INFORMATION REQUIRED
• SAME AS MINES
OCEAN DISPOSAL
SLUDGE CHARACTERIZATION
ANALYTICAL AND SAMPLING REVIEW
PHASE III
• RECOMMENDATIONS FOR SIMULATION AND DEMONSTRATION TEST PROGRAM
CHEMICAL
• SULFITE LEVELS AND CHEMICAL OXYGEN DEMAND OF SLUDGES AND LEACHATES
• SOLUBILITY AND OXIDATION RATES OF CALCIUM SULFITE IN SEAWATER AND GROUND-WATER
• LEACHING DATA AND EFFECTS OF TREATMENT ON POLLUTANT MOBILITY
• EFFECTS OF ASH CONTENT ON LEVELS OF TRACE ELEMENTS IN SLUDGE
ENGINEERING AND PHYSICAL
• LIQUID AND PLASTIC LIMITS INDICES
• CONSOLIDATION TESTS
• TRIAXIAL COMPRESSION TESTS
• EFFECTS OF CRYSTAL STRUCTURE AND FLY ASH ON SLUDGE DEWATERING CHARACTERISTICS
MINE DISPOSAL
• APPLICABILITY TO OCEAN AND MINE DISPOSAL
• DEFINE MODIFICATIONS AS APPROPRIATE
• VERIFY PROCEDURES FOR PHASE III USE
LABORATORY TESTING (mine)
REFINEMENT OF IMPACT ASSESSMENT
SYSTEM DESIGNS AND ECONOMICS
• TOS, LEACHABILITY AND OXIDATION
• CORROSION POTENTIAL (steel and concrete)
• SO2 EVOLUTION POTENTIAL
• SLUDGE FREEZE-THAW EFFECTS
• SIGNIFICANCE OF GEOTECHNICAL ISSUES
• EFFECT OF HYDROGEOLOGY ON GROUND WATER QUALITY
• UPDATE REGULATORY ASSESSMENTS
• FUGITIVE EMISSIONS AND OTHER HEALTH EFFECTS
• PRELIMINARY ENGINEERING DESIGNS (total of two options)
• CAPITAL AND OPERATING COST ESTIMATES, TRADEOFFS, AND COST SENSITIVITY
• COMPARE WITH PUBLISHED LANDFILL AND POND DISPOSAL ESTIMATES

Figure 49. Phase II study outline

TABLE 67. CHEMICAL ANALYSIS OF FGC SLUDGE SAMPLES

Sludge	Wt % Solids[a] (as rec'd)	Analysis (millimoles/g dry solids)						Wt % Acid Insoluble[c]
		Ca	TOS[b]	SO_4	Na	Mg	Cl	
Dual alkali, clean filter cake (CEA-1)	54	7.15	5.52	0.97	0.43	0.25	0.027	0.00
Dual alkali, fly ash-containing filter cake (CEA-2)	57	4.45	2.66	0.87	0.22	0.22	0.031	30.8
Direct lime, fly ash-containing centrifuge cake (TVA-1)	63	4.59	3.85	0.70	<0.03	0.045	0.052	35.2
Direct lime, clean, filter cake (TVA-2)	52	7.22	5.76	1.37	<0.03	0.074	0.030	0.83
Direct lime (carbide), filter cake (LGE-1)	47	6.99	5.89	0.52	<0.02	0.23	0.008	2.94
Gypsum (CIC-1)	83	6.05	not done	6.04	<0.02	0.012	0.004	0.30

[a] Weight percent dry solids in the "as received" wet cakes.

[b] Total oxidizable sulfur (calculated as sulfite).

[c] Insoluble in 1 molar HCl.

b. Physical and engineering properties methods

c. Chemical analysis of groundwater and seawater

d. Sampling techniques for monitoring groundwater and seawater

It was also recognized that there are no typical mine conditions and that wide variations exist. Therefore, in this phase, the ranges of likely mine conditions and the sensitivity of any conditions are defined as being representative in the Phase I report. Impacts and allowable disposal amounts will depend on the site specific nature of FGD sludge, its placement and treatment technique, mine hydrogeology, and mine geology. Therefore, the hydrogeological and geochemical aspects of mine disposal are being given major emphasis in the impact assessment. Other effects are outlined in Figure 49.

In reviewing the corrosion resistance of concrete to sulfate attack, it was determined that Type V cement should be used because of its low tricalcium aluminate content. An aggregate low in magnesium is needed to avoid sodium attack; coating any embedded steel with epoxy would lessen chloride attack. However, it is not known if sulfites will attack concrete in a manner similar to sulfates. Also synergistic effects, if any, that may occur when both sulfates and chlorides are present near concrete are also unknown. It was reported that the state of knowledge for some FGD sludge parameters is inadequate to accurately define the impact of sludge on concrete and embedded steel. It was noted that any tests using Type V cement require three months curing time before a concrete specimen can be subjected to exposure testing in sludge liquors. Also, any in-field demonstration using corrosion-resistant concrete must employ this three-month curing period. Use of a Type V cement, epoxy-coated rods, and a pure limestone aggregate with a low water-to-cement ratio may increase materials cost by about 25 percent.

In addition, other efforts during the first half of Phase II have been to finalize plans and methods for sludge TOS and dissolution methods and to incorporate modifications to the Phase I report in accordance with the recent passage of the RCRA of 1976 and the broadened legislative coverage of the State of Pennsylvania.

In the ocean assessment task, water column drop tests are being performed in order to determine sludge cohesiveness and behavior. The effect of water content in the sludge is being investigated, as well as the effects of rewetting and resettling. Preliminary results indicate that lime sludge is more cohesive than double alkali; both types eroded more easily than dredged river bottom material that was used as a basis of comparison. Several other sludges are to be tested, and quantitative data will then be available.

Laboratory programs of bottom dispersion tests have been completed, and the results are being analyzed. These tests were directed toward determining the overall stability of sludges on the ocean floor and, in particular, the critical velocity for sludge erosion and resuspension. In general, they tend to be consistent with the cohesive properties observed.

The sludge dissolution and TOS oxidation apparatus was checked in simulated seawater tests. Both seawater and groundwater tests will be performed.

Refinement of Phase I impact assessment is under way. At present, the bases for economic evaluation of promising alternatives have not been fully defined and are not available for inclusion in this report.

5.5 NEW FGC WASTE UTILIZATION METHODS

Utilization projects include development of (1) a process for FGC waste conversion (to sulfur and calcium carbonate), (2) pilot studies of fertilizer production (using the waste as a filter material and a source of sulfur), and (3) use of FGC waste in an alumina extraction process.

5.5.1 Lime and Limestone Scrubbing Waste Conversion Pilot Studies (Pullman Kellogg)

A study is planned to evaluate the Kel-S process, which produces elemental sulfur as an alternative to throwaway disposal of FGD lime and limestone wastes. The project will be approximately 11 months in duration. It involves a cost-shared contract with Pullman Kellogg, Houston, Texas, to conduct pilot-plant scale evaluation of several key steps in the Kel-S process. The project is expected to be initiated in 1977.

The process converts FGD wastes obtained from lime and limestone scrubbers to elemental sulfur. It also produces calcium carbonate, $CaCO_3$, which can be recycled in the SO_2 scrubbing system. FGD waste will be reduced, using coal as the reactant, to calcium sulfide, CaS, in a continuously rotating kiln. The CaS is then reacted with hydrogen sulfide, H_2S, which is available from the recovery unit and forms calcium hydrosulfide, $Ca(HS)_2$. The $Ca(HS)_2$ is dissolved in water and the solution is filtered. The cycle is closed by reacting the $Ca(HS)_2$ with CO_2-rich gas available from the drying kiln. The reaction with CO_2 forms H_2S and also $CaCO_3$, which is precipitated. Half of the H_2S is returned to react with the CaS, and the remainder is converted to elemental sulfur in a conventional Claus unit. The $CaCO_3$ is recycled to the scrubber system.

It is expected that design and operating data will be obtained to permit scaleup of the process to a prototype integrated system that can be operated in conjunction with a power plant FGC system.

5.5.2 Fertilizer Production Using Lime and Limestone Scrubbing Wastes (TVA)

The use of lime and limestone scrubbing wastes as a filler material and source of sulfur in granular fertilizers is being evaluated.

The work is being performed by TVA, Office of Agricultural and Chemical Development, Muscle Shoals, Alabama, as part of an interagency agreement directed toward the evaluation of the utilization or disposal of FGC wastes.

Results from previous TVA bench-scale laboratory tests and small field plot application tests with rye grass were sufficiently promising to warrant additional work on a pilot-plant production basis. In addition to the pilot plant evaluation, the technical, economic, and environmental impacts will be studied as a result of producing and using granular fertilizer from scrubber wastes. Specific tasks include (1) determining compatibility factors involved in mixing and storing the fertilizer with conventional fertilizer, (2) conducting of field plot tests with the pilot-plant-produced fertilizer, and (3) assessing the effects of trace and toxic materials relative to those in conventional fertilizers. Marketing studies of the scrubber-waste-based fertilizer are also planned.

The process basically consists of mixing phosphoric acid, H_3PO_4, and gaseous ammonia with a typical dewatered sludge produced from lime-limestone scrubbers. The temperature of the mixture is maintained at approximately 200°F while phosphoric acid and ammonia are metered in at a predetermined rate. The sludge, acid, and ammonia mixture is maintained slightly acidic to prevent solidifying in the preneutralizer. After the desired amount of acid and base are added, the hot mixture is transferred to an ammoniator-granulator, where further ammoniation causes the slurry to solidify and form a granular material. A certain amount of partially dry, undersized material is recycled to the ammoniator-granulator to facilitate proper granulation. The granular material discharged from the ammoniator-granulator is dried, cooled, and screened to obtain a fertilizer product with desirable nutrient and physical characterization.

The pilot plant production and the storage compatibility tests are scheduled for completion in 1977. Long-term agronomic testing is planned to begin in 1977 and extend through 1979.

A flow diagram of a typical pilot plant process is shown in Figure 50. The pilot plant for this study is rated at 3000 lb/hr.

During initial pilot plant preneutralizer tests using sludge produced at the 1-MW limestone pilot unit located at the TVA Colbert Steam Plant, severe foaming occurred during the introduction of sludge, phosphoric acid, and ammonia into the preneutralizer. The preneutralizer was then operated with only the acid and ammonia in the conventional ammonium phosphate mode. The sludge and the ammonium phosphate from the preneutralizer were then fed to the drum granulator. A number of sludge feed rates were tried, and those resulting in acceptable granulation rates have been defined.

Construction of a specially designed preneutralizer to eliminate the problems encountered was completed. It includes alternative methods and locations for adding the sludge, acid, and ammonia. Improved agitation, foam breaking methods, and insulation were included. One of the

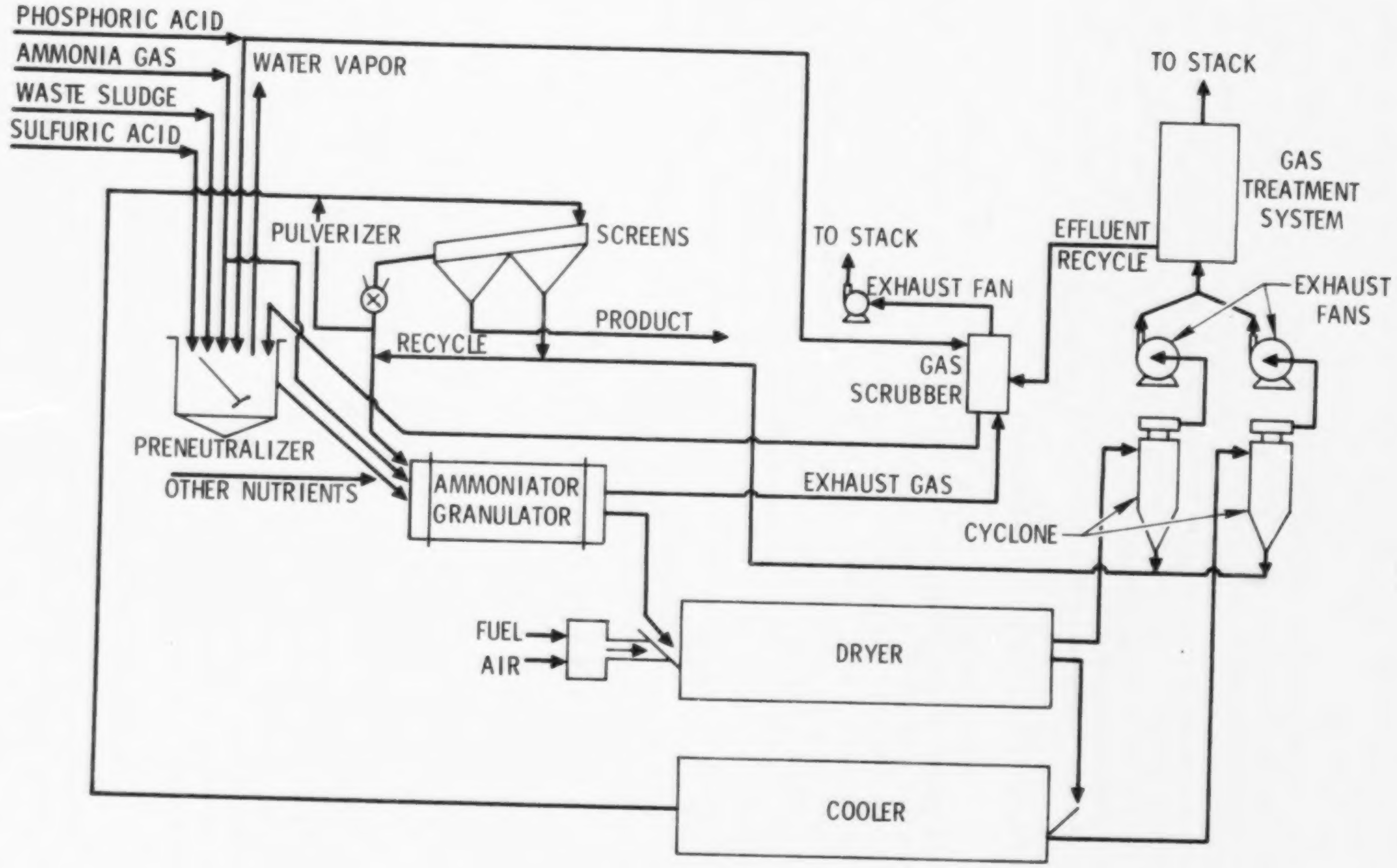

PHOSPHORIC ACID
AMMONIA GAS
WASTE SLUDGE
SULFURIC ACID
WATER VAPOR
PULVERIZER
SCREENS
PRODUCT
RECYCLE
PRENEUTRALIZER
OTHER NUTRIENTS
AMMONIATOR GRANULATOR
FUEL
AIR
DRYER
COOLER
TO STACK
EXHAUST FAN
GAS SCRUBBER
EXHAUST GAS
EFFLUENT RECYCLE
TO STACK
GAS TREATMENT SYSTEM
EXHAUST FANS
CYCLONE

Figure 50. Process flowsheet for producing solid granular fertilizer material from scrubber sludge.

objectives in the development of the preneutralizer modifications is the effective utilization of the heat of reaction in reducing the water content of the incoming sludge.

Initial testing with the modified preneutralizer resulted in an unacceptable sulfur loss ranging from 78 to 90 weight percent and an ammonia loss of 34 to 61 weight percent based on input quantities.

The losses are suspected to result from a reaction between calcium sulfite in the sludge and phosphoric acid.

Calcium sulfite + phosphoric acid ⟶ calcium phosphate + sulfurous acid

$$3CaSO_3 + 2H_3PO_4 \longrightarrow Ca_3(PO_4)_2 + 3H_2SO_3 \qquad (1)$$

Sulfurous acid + ammonia ⟶ ammonium sulfite

$$H_2SO_3 + 2NH_3 \longrightarrow (NH_4)_2SO_3 \qquad (2)$$

Laboratory tests indicated that the reaction defined by Eq. (1) occurs readily at room temperature. Also, past pilot plant experience has shown that ammonium sulfite formed as in Eq. (2) can be easily lost as a very fine particulate in the gas stream. This loss would be enhanced by the agitation and by the stripping action of the water being boiled off in the preneutralizer.

It is expected that these unwanted reactions can be prevented by either neutralizing the phosphoric acid before it comes into contact with the sludge or by oxidizing the calcium sulfite to calcium sulfate before feeding to the preneutralizer. Therefore, tests are being planned to determine the feasibility of using oxidized sludge in the preneutralizer.

Additional tests (Table 68) were conducted to define preneutralizer operating conditions. These included the effect on ammonia-to-phosphoric acid ratios and the location of the sludge feed and its flow rate.

Problems including release of SO_2, sparger plugging, and temperature and fluidity control were encountered under the conditions tested.

It is planned to conduct tests at a pH of 6.5, where the fluidity of the product sludge is expected to be at an acceptable level with the promotion of di-ammonium phosphate rather than mono-ammonium phosphate

TABLE 68. PRENEUTRALIZER TEST CONDITIONS

NH_3 to H_3PO_4 mol Ratio	pH	Sludge Feed Rate, gpm	Remarks
0.3	1.6	1.0	SO_2 released from system. Gas spargers plugged with slurry due to low gas feed rate.
1.5	6.5	1.5 - 2.0	Temperature in preneutralizer could not be maintained at 2 gpm.
1.5	6.5	1.5	Difficulty encountered in controlling fluidity of product slurry.
1.5	6.5	1.5	Relocated sludge feed from bottom to top of preneutralizer. Change did not improve operation.

that is formed at a pH of 1.6. Some preliminary testing at a pH of 6.5 has shown that mixing is important, and some SO_2 has been driven off as a result of regions with low pH.

5.5.3 Utilization of Lime and Limestone Scrubbing Waste in a New Extraction Process (TRW)

TRW has completed a preliminary process design and economic evaluation of a method for the utilization of lime and limestone scrubbing wastes, the wastes being a source of calcium in the extraction of alumina from low-grade domestic ores such as clays or coal ash (Figure 51). The other principal feedstocks for the process are soda ash and coal. The products are alumina for use in aluminum production, elemental sulfur, and dicalcium silicate, an alternative material for use in producing portland cement.

Present alumina production in the United States is based exclusively upon the Bayer process or its variations which utilize bauxitic ore. Domestic production of bauxite is approximately 10 percent of consumption, with dependence for the remaining supply centered on the Caribbean area and other sources external to the United States. Domestic reserves have been estimated (1965) at 45 million (MM) tons or 0.8 percent of the total world supply. The annual U.S. demand for aluminum metal is expected to be at least 21.2 MM tons by the year 2000 or approximately equivalent to 41.4 MM tons of bauxite ore. Other sources of aluminum exist in abundance within the continental United States. However, these are in the form of low-grade clay deposits or thin or deeply buried bauxite deposits. With the insufficiency of U.S. domestic bauxite reserves, a study to investigate alternative mineral sources of aluminum and related processes for its extraction was conducted.

The process design is based on colocating the conceptual processing plant with a 1000-MW coal burning power plant in order to receive more than 1,000,000 tons per year (TPY) of lime or limestone FGC scrubber wastes. In addition to scrubber wastes, the process will require, on an annual basis, 12,000 tons of soda ash, 300,000 tons of clay, and 273,000 tons of coal to produce 70,000 tons of alumina, 156,000 tons of sulfur, and 625,000 tons of dicalcium silicate. Dicalcium silicate would be used to feed a cement manufacturing facility producing 860,000 tons of portland cement per year.

The results of this study indicate that an alumina extraction process employing calcium sulfate and sulfite sludge, sodium carbonate, and kaolin clay as reactants could be commercially feasible under present economic conditions provided that the alumina extraction plant includes a cement producing facility which utilizes the dicalcium silicate by-product from the alumina extraction process. Should bauxite prices escalate, the estimated selling price for alumina as output from an alumina plant not possessing a cement facility may become competitive. Each of the above conclusions are based upon a sulfur credit of $10.00 per ton and a sludge

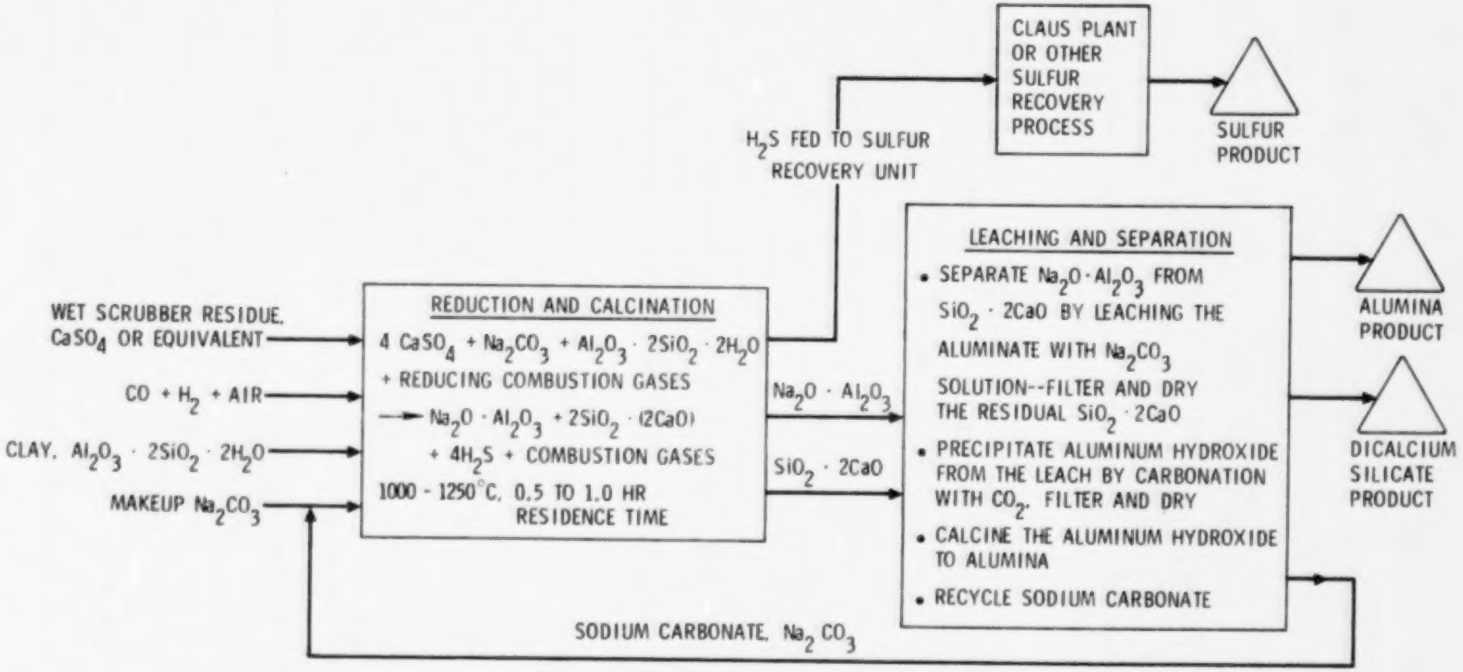

WET SCRUBBER RESIDUE, $CaSO_4$ OR EQUIVALENT
$CO + H_2 + AIR$
CLAY, $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$
MAKEUP Na_2CO_3
REDUCTION AND CALCINATION
$4\ CaSO_4 + Na_2CO_3 + Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$
+ REDUCING COMBUSTION GASES
$\longrightarrow Na_2O \cdot Al_2O_3 + 2SiO_2 \cdot (2CaO)$
$+ 4H_2S$ + COMBUSTION GASES
1000 - 1250°C, 0.5 TO 1.0 HR RESIDENCE TIME
H_2S FED TO SULFUR RECOVERY UNIT
CLAUS PLANT OR OTHER SULFUR RECOVERY PROCESS
SULFUR PRODUCT
$Na_2O \cdot Al_2O_3$
$SiO_2 \cdot 2CaO$
LEACHING AND SEPARATION
• SEPARATE $Na_2O \cdot Al_2O_3$ FROM $SiO_2 \cdot 2CaO$ BY LEACHING THE ALUMINATE WITH Na_2CO_3 SOLUTION--FILTER AND DRY THE RESIDUAL $SiO_2 \cdot 2CaO$
• PRECIPITATE ALUMINUM HYDROXIDE FROM THE LEACH BY CARBONATION WITH CO_2. FILTER AND DRY
• CALCINE THE ALUMINUM HYDROXIDE TO ALUMINA
• RECYCLE SODIUM CARBONATE
ALUMINA PRODUCT
DICALCIUM SILICATE PRODUCT
SODIUM CARBONATE, $Na_2\ CO_3$

Figure 51. Proposed extraction process

disposal credit of $5.00 per wet ton (50 percent solids). One of the utilization processes considered more viable is illustrated in Figure 52. The selling price for alumina as estimated for this arrangement is $89 per ton. This value may be compared with the present market value of $160 per ton (July 1976) and the estimated selling price of $248 per ton, 10 percent discounted cash flow (DCF) from an unattached alumina plant.

The required selling price for the alumina produced at 10 DCF would range from $178 to $309 per ton as a function of sludge removal credit, exclusive of cement manufacture. However, if this alumina plant were colocated with a 860,000 TPY portland cement plant selling cement at $40 per ton, the alumina produced would have a selling price range of $19 to $165 per ton at 10 percent DCF, depending on sludge removal credit. The alumina selling price is dependent upon the values of several parameters. Chief among these are the amount of water in the scrubber sludge, the sludge credit taken in the accounting, the price of coal to the process, the selling price of sulfur, and the plant capital and operating costs.

The chemistry of the process is similar to the lime-soda-sinter reaction except that the reaction proceeds in a reducing rather than an oxidizing atmosphere. The reaction may be summarized as follows:

$$\text{Sludge} + \text{soda} + \text{clay} \longrightarrow \text{soluble sodium aluminate} + \text{insoluble dicalcium silicate}$$

or

$$4CaSO_4 + Na_2CO_3 + Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O + \text{reducing combustion gases} \longrightarrow Na_2O \cdot Al_2O_3 + 2SiO_2 \cdot (2CaO) + 4H_2S + \text{combustion gases} \qquad (3)$$

It has been assumed that this reaction will occur at 1200°C with coal and a less than stoichiometric amount of oxygen. However, the chemical functioning of this process is predicated upon several technical assumptions which require laboratory verification before concluding that the potential for an extraction process exists. TRW laboratory recommends bench-scale investigations to confirm the following:

a. Reactions of soda, alumina, calcium, and silica to form dicalcium silicate and sodium aluminate will proceed in a reducing atmosphere to achieve high yields.

b. Reaction rates are sufficiently fast to be practical.

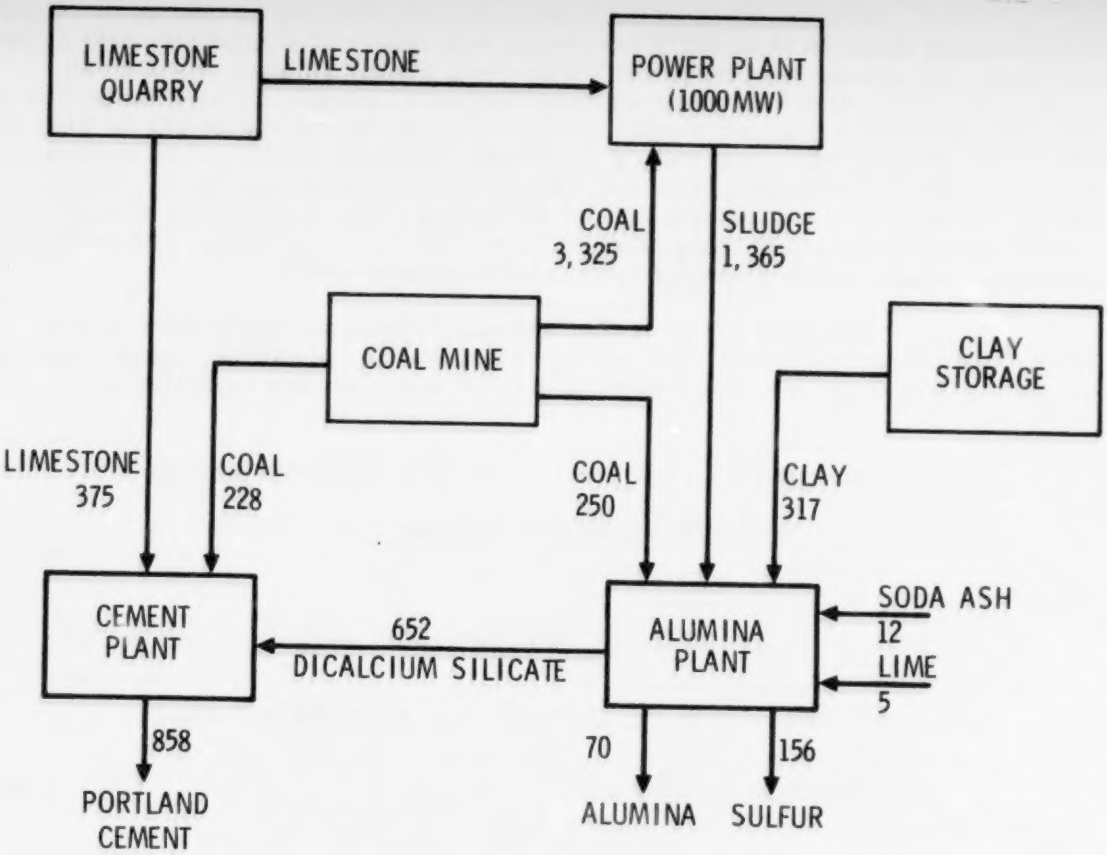

LIMESTONE QUARRY
LIMESTONE
POWER PLANT (1000 MW)
COAL 3,325
SLUDGE 1,365
COAL MINE
CLAY STORAGE
LIMESTONE 375
COAL 228
COAL 250
CLAY 317
CEMENT PLANT
652
DICALCIUM SILICATE
ALUMINA PLANT
SODA ASH 12
LIME 5
858
PORTLAND CEMENT
70
ALUMINA
156
SULFUR

Figure 52. Total utilization concept (quantities in 10^3 tons/yr)

c. **Side reactions do not occur which inhibit the formation of soluble sodium aluminate and thus negate the output of alumina.**

d. Coal in the proper amounts can be used to produce a reducing atmosphere.

e. The dicalcium silicate by-product possesses the necessary mechanical properties for compatibility with standard cement manufacturing.

Other elements of the process not dependent upon the referenced assumptions have been demonstrated in earlier work by the Bureau of Mines (Refs. 24 and 25) and TRW Systems, Inc. (Ref. 26). Given the laboratory demonstration of the validity of the process chemistry assumptions, TRW considers sufficient technical justification exists to proceed with a development program. No unusual equipment has been identified, and plant construction can be accomplished with standard items.

TRW has also recommended that an alternative processing method be considered for study where the principal product is cement. It would use sand and lime or limestone scrubber sludge as primary feedstocks. It would require less capital than the alumina extraction process, and such a process would be less energy intensive.

5.6 IMPROVEMENT OF OVERALL POWER PLANT WASTE USE

The program to improve power plant water use effort comprises a study of methods to minimize water losses and to recycle or reuse waste water discharges.

5.6.1 Water Recycle and Reuse Alternatives in Coal-Fired Steam-Electric Power Plants (Radian)

A technical and economic study is being conducted by Radian, Inc., Austin, Texas, to assess the options for the recycle or reuse and treatment of water from coal-fired utility power plants. The primary objective is to define ways to minimize water consumption and the discharges of waste water.

Three plants were selected initially for water system characterization and detailed analysis (Ref. 1). Since the last annual report, two additional power plants have been added to the study. The analyses include an evaluation of the technical and economic feasibility of various water recycle and reuse options. The plants were chosen to represent regions in the United States where water recycle or reuse would be advantageous because of high water costs, limited availability, or treatment and disposal problems. Other screening criteria included location, availability, site characteristics, and timing.

The first three sites selected were the Four Corners plant of Arizona Public Service, Comanche of Public Service of Colorado, and Bowen of Georgia Power Company. The study has been completed for these locations. During the past year, similar studies were initiated for the Colstrip plant of Montana Power Company and Montour of Pennsylvania Power and Light Company. Water and ash samples from these sites have been taken and are in the process of being analyzed. Analyses were completed for the first three locations and used in the evaluation. Precipitation kinetic experiments for $CaCo_3$ and $Mg(OH)_2$ were conducted to define their critical scaling limits. Characterization of the ash was performed to determine CO_2 mass transfer between the atmosphere, process vessels, and ash ponds. Using this input data, a computer model was prepared to simulate the existing plant operations. With the model, predictions of plant operations were made for the first three sites. After comparisons with actual plant operations were made to verify the validity of the models, they were used in the technical assessment of various water recycle and reuse alternatives.

The technical assessment included the evaluation of various water recycle and reuse options and strategies for each of the representative plants on the basis of design or design installation, operability, and treatment effectiveness. The sensitivity to various parameters was determined and reported. Cost estimates including capital, installation, and operating costs of the most attractive viable options as defined by the technical assessment were made, and the overall optimum recycle or reuse option based on technical and economic considerations for each of the three plants was defined. The results of the study including recommendations for each plant, further assessments, testing, or field demonstrations will be included in the final report, which will be published upon completion of the analyses for the Colstrip and Montour plants.

The characterization of the existing operations and the proposed recycle and reuse alternatives are summarized in this section. Details are reported in References 27 through 29. The basic characteristics of each plant are summarized in Table 69.

5.6.1.1 Four Corners Station

The Arizona Public Service Company (APS) Four Corners station is a five-unit 2150-MW coal-fired electric generating plant located near Farmington, New Mexico. The coal burned at Four Corners contains approximately 20 percent ash and 0.5 to 1.0 percent sulfur and has a heating value of about 9300 Btu/lb. The plant uses a cooling pond and a bottom ash wet sluicing for all units, particulate wet scrubbing for Units 1 through 3, and ESP for Units 4 and 5 (dry ash disposal). Makeup water for the plant is taken from the San Juan River and stored in Morgan Lake, which serves as the source for all water used in the system. A periodic blowdown is taken from Morgan Lake to control the TDS concentration. This blowdown is discharged to the Chaco River which flows into the San Juan River.

Table 69. BASIC CHARACTERISTICS OF POWER PLANTS

Utility	Station	Location	Capacity, MW	Type of Cooling[b]	Ash Handling[c]	Particle Control[d]	SO_2 Control[e]
Arizona Public Service	Four Corners	Farmington, New Mexico	1600	CP	WSB WSF	Cyclones, ESP, venturi	UC
Public Service of Colorado	Comanche	Pueblo, Colorado	350	WCT	WSB	ESP	None
Georgia Power Co.	Bowen	Taylorsville, Georgia	1595[f]	WCT	WSB WSF	ESP	None

[a] Reference 20.

[b] Wet cooling tower (WCT); cooling pond (CP).

[c] Wet sluicing of bottom ash (WSB); wet sluicing of fly ash (WSF).

[d] Electrostatic precipitator (ESP).

[e] Under construction (UC).

[f] Plant capacity as reported in Federal Power Commission (FPC) Form 67 data sheet; present capacity is 3200 MW (4 units).

Cooling water, bottom ash sluicing water, boiler makeup water, and makeup water for the particulate scrubbing system are taken from Morgan Lake. In addition to the blowdown stream from Morgan Lake, water leaves the plant through evaporation from the lake, evaporation from the ash pond, evaporation in the scrubbers, and ash pond overflow. Some vaporization also occurs in bottom ash sluicing operations as a result of the high ash temperature.

Based on computer model simulations, potential scaling conditions were found at several points in the scrubbing system for low (2 percent) solids operation. The model had been previously found to adequately represent the existing plant operations when its output was compared to the chemical analyses of water samples. The scrubber effluent, thickener overflow, and thickener underflow all were identified as showing $CaSO_4 \cdot 2H_2O$ relative saturations above 1.3, indicating a tendency to form gypsum scale. No calcium carbonate scaling was noted. A simulation of high (9 percent) solids operation showed increased scaling potential in the system.

Four alternatives were studied for the particulate scrubbing system:

a. Use existing tanks as solid-liquid reaction vessels

b. Substantially increase tank volume

c. Recycle ash pond overflow

d. Reduce flue gas fly ash content into scrubbers

The study focused primarily on the particulate wet scrubbing system and subsequent ash disposal for Units 1 through 3. Water is recycled in the cooling and bottom ash sluicing systems, and the potential for water recycle-reuse alternatives in these systems was considered slight. Also, since scaling problems have been encountered in the scrubbing system, the study of recycle and reuse alternatives at Four Corners addressed the causes and potential solutions of these problems.

Based on the results of simulating the first alternative, it was reported that the present system tankage capacity is not sufficient to allow ample gypsum precipitation to prevent scaling.

In the second alternative, increasing the tank capacity to 37,500 m^3 (1.33×10^6 ft^3) was simulated. Gypsum relative saturations were reduced to levels below the critical level required for the onset of scaling. Two cases were studied with different scrubber liquid-to-gas ratios (L/G). The existing L/G of 4.7 ℓ/nm^3 (18.7 gal/1000 acf) gave a scrubber bottoms pH of 2.9 and an L/G of 10.0 ℓ/nm^3 (39.8 gal/1000 acf) gave a pH of 3.9 (assuming 50 percent SO_2 removal), indicating that higher L/G's are desirable for corrosion control.

Simulating the third alternative, recycling the ash pond overflow to the scrubbing system, it was found that the pond overflow has no significant effect on the gypsum relative saturations in the system. However, the water makeup requirements are reduced from 70.7 ℓ/sec (1122 gpm) for alternative two to about 50.8 ℓ/sec (807 gpm). Also, a simulation with ash pond overflow recycle using a reaction tank volume of 21,200 m^3 (7.5×10^5 ft^3) showed that a more reasonable reaction tank volume can be utilized. This simulation showed a gypsum relative saturation of 1.19 in the scrubber effluent slurry.

The fourth alternative indicated that reaction tank volume could be decreased further if portions of the fly ash were removed by dry methods prior to the scrubbing system. A volume of 8900 m^3 (3.14×10^5 ft^3) was used to obtain a gypsum relative saturation of 1.19 in the scrubber effluent (60 percent of fly ash removed prior to scrubber). Water makeup requirements were also reduced to 41.0 ℓ/sec (650 gpm).

The resulting rough-cost estimates of the technically feasible options, alternatives (a) through (c), indicated that two to three million dollars would be required to upgrade the particulate scrubbing system so that scaling potential is eliminated and water requirements reduced. Installed costs for the least expensive alternatives was case two of alternative (c) (recycle ash pond overflow, reduced reaction tank volume), which were $\$2.491 \times 10^6$. This was followed closely by option (c), $\$2.546 \times 10^6$. Alternative (b), cases one and two, and alternative (c), case one, showed similar installed costs of $\$2.708$ to 3.313×10^6. Energy consumption was not greatly different between alternatives although alternative (c), case one (increased tank volume, low L/G), indicated a lower energy requirement of about 2370 kWh/hr less than the other alternatives.

5.6.1.2 Comanche Plant

The Public Service of Colorado Comanche generating station is a coal-fired system composed of two units, each having a 350-MW capacity, and is located near Pueblo, Colorado. The basic water flow schematics are the same for both units. The cooling system uses wet cooling towers to discharge heat. The ash removal system consists of wet sluicing for bottom ash and ESP and subsequent dry disposal for the fly ash. The bottom ash slurry is sent to ash ponds for disposal.

Under existing operations, the water entering the system is first taken from the Arkansas River and stored in a raw water reservoir. From the reservoir, a small portion of the raw water (about 7 ℓ/sec or 105 gpm) is sent to the coal handling facilities for dust suppression. Another portion of the flow from the reservoir is sent to the ash removal system to sluice bottom ash into the ash ponds. The remainder of the raw water leaving the reservoir is sent to the Comanche lime treatment facility to reduce the calcium hardness. The lime sludge produced during the softening process is sent to a special ash pond, which is kept separate from the ponds receiving bottom ash slurries. The softened water is used for service water and for makeup water for the two cooling systems.

The water effluent leaves the system via the overflow from the final polishing pond, which is fed by the two boiler blowdown streams, the lime sludge disposal pond overflow, and the two bottom ash disposal pond overflows. The final polishing pond effluent is sent to the St. Charles River. The remaining system water losses are cooling tower evaporation and drift and other evaporative losses.

5.6.1.2.1 Cooling System

The station has two cooling systems, one for each unit. The systems are identical and employ wet cooling towers for evaporative cooling.

The circulating cooling water characteristics are controlled by the makeup water composition and by the amount of chemical additives introduced into the system. Sulfuric acid is added for pH control, and zinc polyphosphate is added to inhibit scaling.

The blowdown stream is maintained at a rate sufficient to keep dissolved species from concentrating to the point of saturation. Otherwise, scaling of the line and equipment could result. Present operation of the Comanche cooling system maintains the blowdown rate so that the makeup water is concentrated about five times, i.e., the number of times that dissolved species in the makeup water are concentrated in the circulating water.

5.6.1.2.2 Ash Disposal System

The ash disposal system consists of two ash ponds of about 5060 m^2 (54,500 ft^2) each. Only bottom ash is being sluiced into the ponds at present. The fly ash is trucked away in a dry form.

The bottom ash stream sluiced to the ash ponds contains about one weight percent solids. The sluicing is intermittent; bottom ash is removed from the ash hopper about six hours per day. The sluice water comes from two sources, blowdown from the cooling system and untreated water from the plant raw water reservoir.

Part of the cooling system blowdown stream is diverted for use as boiler refractory cooling water. This water subsequently flows down into the bottom ash hoppers where an overflow stream is sent to the ash ponds. But when bottom ash is being removed, the refractory cooling water goes out in the bottom ash sluice stream.

The bottom ash sluice stream flow rate to the ash pond is about 210 cm/sec (7 ft/sec). The sluice lines for the two boiler units are 760 and 590 m (2500 and 1930 ft) long, giving line retention times of about 5.9 and 4.6 minutes, respectively.

5.6.1.2.3 Technical Alternatives

The water recycle-reuse alternatives for the Comanche plant are summarized as follows. For purposes of the simulation, the water streams were divided into two systems, the cooling system and the ash handling system. The operating characteristics of the cooling system were examined first. Then the ash handling system was analyzed in the context of the possible range of cooling system blowdown streams available for sluicing. This resulted in evaluating water recycle and reuse alternatives on the basis of the Comanche water system.

All of the alternative cooling system simulations were performed for summer operation of the cooling towers because summer conditions represent the case of maximum blowdown rates.

The calculated $CaCO_3$ and $CaSO_4 \cdot 2H_2O$ relative saturations in the recirculating cooling water (8.2×10^{-4} and 0.252, respectively) indicate that the cycles of concentration may be significantly increased without forming calcium carbonate or gypsum scale. However, a high level of the silica concentration exists in the makeup water and may require some form of silica removal, such as lime and soda ash treatment, in order to prevent silica scaling at higher cycles of concentration. Pilot or bench scale studies to more accurately quantify silica scaling potentials should be performed before increasing the cycles of concentration in the cooling system.

In evaluating cooling system alternatives, simulations were conducted to determine the effects of operating at increased cycles of concentration in the towers. Results of simulating cooling tower operations at 5.0, 7.6 and 15.0 cycles of concentration were obtained. Also, system sensitivity to composition changes in the makeup water were investigated by assuming twice the sulfate concentration in the makeup water as that found in the water sample from the plant for 5.0, 7.6, and 13.0 cycles of concentration.

Three alternatives were examined for ash sluicing. The first case involved the use of a cooling system blowdown from the towers operating at five cycles of concentration to sluice fly ash and bottom ash on a once-through basis. Additional cases were run with this configuration to determine the effects of CO_2 mass transfer in the ash pond and the sluice tank. No gypsum scale potential was identified in any of the once-through sluicing cases, but potential scaling of $CaCO_3$ and $Mg(OH)_2$ was found to be present.

However, the possibility was reported that the fly ash slurry line can be kept free of plugging by the addition of a fly ash slurry reaction tank and by frequent flushing with water of pH 6 to 7. Pilot or bench-scale studies are needed in order to size the reaction tank and determine the quantity of wash water required before implementing fly ash sluicing. This alternative will result in an ash pond overflow of about 32.7 ℓ/sec (518 gpm) for each unit as compared to the existing configuration pond overflow rate of about 78 ℓ/sec (1233 gpm). The other two alternatives included the recirculation of ash pond liquor and sluicing of bottom ash and dry fly ash disposal. Fly ash sluicing is included as well as the existing bottom ash sluicing for the first two alternatives. For fly ash sluicing, the effects of CO_2 transfer in the pond and in the sluice tank were examined, as well as the scaling potentials of the system.

From the results of the cooling tower and ash sluice system simulations conducted, two alternatives for reducing plant discharges with fly ash sluicing in the system were reported as technically feasible:

a. Cooling system operation at 5.0 cycles of concentration (essentially the existing operations) with once-through ash sluicing. The ash pond overflow may be discharged after a pH adjustment or can be treated with a brine concentrator and reverse osmosis unit, with the clean water recycled to the boiler and cooling tower makeup systems.

b. Cooling system operation at 7.6 cycles of concentration with the sluicing of bottom ash by use of recycled ash pond water. The fly ash would be sluiced by cooling system blowdown water, 50 percent of which was previously treated with brine concentration to lower the calcium and sulfate in the ash sluicing makeup water.

A third alternative was also reported in which dry fly ash was disposed as is currently done at Comanche. The cooling towers may be operated at 8.4 cycles of concentration (with lime-soda ash treatment for silica removal if necessary) providing 16.4 ℓ/sec (260 gpm) blowdown for boiler refractory cooling for each unit. This water may then be used to sluice bottom ash on a once-through basis, resulting in an ash pond overflow or about 15.1 ℓ/sec (240 gpm) per unit. Zero discharge may be achieved with this alternative by treating the overflow by brine concentration and recycling the clean water to the boiler and cooling tower makeup systems.

The first alternative requires the addition of reaction tanks upstream of the fly ash sluice line to minimize $CaCO_3$ and $Mg(OH)_2$ scale formation in the line. Adjustment of the pH of the ash pond overflow may be required, depending on the amount of CO_2 transfer occurring in the ash pond. The calculated pH for equilibrium with respect to CO_2 between the pond and the atmosphere is 7.9, but the value for no CO_2 transfer is 12.7.

The second alternative also includes adding reaction tanks in the fly ash sluice system, as in the first alternative. Also, recycle lines and pumps are required to return a portion of the ash pond liquor for sluicing. This alternative involves operating the cooling system at 7.6 cycles of concentration, which reduces the ash pond overflow to 14.4 ℓ/sec (229 gpm) for each unit. However, cooling system scaling may result because of silica. Chemical studies are needed to be undertaken to investigate if scaling will occur.

If scaling were to occur at the increased level of concentration, the silicate concentrations must be lowered by lime-soda ash softening of the cooling system makeup water instead of solely lime treatment. Approximately

50 percent of the cooling tower blowdown must be treated to remove calcium and sulfate to avoid gypsum scaling in the sluice line.

The second alternative can achieve zero-discharge by treatment of the ash pond overflow by a brine concentrator and reverse osmosis unit. Discharge of the ash pond overflow may require pH adjustment as in the first alternative, depending on the amount of CO_2 transfer in the pond.

The third alternative is not expected to require pH adjustment of the ash pond overflow before discharge because of the insoluble nature of the bottom ash.

The report (Ref. 28) emphasized here that none of the alternatives should be implemented prior to conducting bench or pilot scale experiments to determine the actual size of the reaction tank required in the sluice system, the quantity and frequency of acid wash water required to minimize $CaCO_3$ and $Mg(OH)_2$ scale formation, and the solubility limits for silica in the cooling tower system.

5.6.1.2.4 Economics of Implementing Alternatives

Rough cost estimates were provided for the various alternatives described in the previous section. The once-through sluice system and the recirculating system using cooling system blowdown to sluice fly ash with 50 percent of the blowdown treated by brine concentration (first alternative) is the least expensive option. Operating the cooling system at 5 cycles of concentration and sluicing the fly ash and bottom ash on a once-through basis is estimated to be $381,000 in capital costs and about $48,000 per year in operating costs.

By operating the cooling systems at 7.6 cycles of concentration with the cooling system blowdown as sluicing makeup (second alternative), the entire plant ash sluice system requires an initial capital cost of about $3.3 million and an operating cost of about $390,000 per year. The costs for silica removal, if required, are not included.

If zero discharge of ash pond overflow is desired, the once-through system becomes more expensive because of the increase in ash pond overflow requiring treatment. A softening, reverse osmosis, and brine concentration system to treat ash pond overflow is estimated to require an additional capital investment of about $8.28 million with an additional operating cost of approximately $1.218 million per year. The total overall costs would be about $8.661 million for capital costs and $1.266 million per year for operating costs.

The additional costs for obtaining zero discharge with the recirculating system would be about $3.700 million for capital costs with $485,000 per year for operating costs. Overall costs for this case total to approximately $7.0 million for capital costs and $877,000 per year for operating costs.

The costs associated with achieving zero discharge with dry fly ash disposal (third alternative) are about \$3.9 million capital costs and \$509,000 per year operating costs. These costs include brine concentration, additional piping, and additional pumping costs.

5.6.1.3 Plant Bowen

The Georgia Power Company Plant Bowen is a four-unit 3180-MW coal-fired electric generating station located near Taylorsville, Georgia. The coal utilized is approximately 11 percent ash and 2.8 percent sulfur with a heating value of about 11,500 Btu/lb. Cooling towers and bottom and fly ash wet sluicing are typical for all of the units.

Makeup water for the plant is taken from the Etowah River and stored in a makeup pond. Water is removed from the makeup pond at a design rate of 1.6×10^5 ℓ/min (52,000 gpm) and used as general service water, boiler makeup, and cooling tower makeup.

The general service water effluent is split so that 5 percent of the flow returns to the makeup pond and 95 percent is used as cooling tower makeup. Water treatment wastes total about 9.5 ℓ/sec (150 gpm) and are pumped to the ash pond. The major water consumers at the Bowen plant are the cooling tower system and the ash handling systems.

5.6.1.3.1 Cooling Tower System

Each of the four units have independent cooling systems with one cooling tower for each unit. Units 1 and 2 are identical (700 MW) and have identical cooling towers. Units 3 and 4 are each rated at 890 MW and also have identical cooling towers. Water circulates between the condenser and the cooling tower of each unit at a rate of 16,280 ℓ/sec (258,400 gpm) for Units 1 and 2 and 19,350 ℓ/sec (310,000 gpm) for Units 3 and 4. A blowdown stream is removed from the circulating water after the condenser. The water removed as blowdown is replenished with fresh makeup water.

The towers operate at about 1.7 cycles of concentration, which is defined as the ratio of blowdown species concentration to makeup species concentrations.

5.6.1.3.2 Ash Handling Systems

Fly ash is collected by ESP at a rate of about 24,200 kg/hr (53,300 lb/hr) from Units 1 and 2 and about 22,500 kg/hr (49,500 lb/hr) from Units 3 and 4. All of the collected fly ash is sluiced on a once-through basis to the ash pond using cooling tower blowdown as sluice water. Sluicing this amount of fly ash at about 7 percent solids requires 350 ℓ/sec (5500 gpm) of water.

Bottom ash is periodically sluiced with cooling tower blowdown to the ash pond also on a once-through basis. Cooling tower blowdown not used for sluicing fly ash is used to sluice the bottom ash at about 1 percent solids. This water is discharged when it is not used to sluice the bottom ash.

5.6.1.3.3 Technical Alternatives

A modular approach was reported to be as used in studying water recycle or reuse alternatives at Bowen. The major plant water systems were divided into two subsystems to form separate process simulations. One subsystem consisted of the cooling towers with associated treatment facilities (where necessary), hold tanks, and condensers. The other subsystem consisted of the ash handling systems. The effects of increasing the cycles of concentration in the cooling towers and of poorer quality makeup water (increased calcium levels) were presented first. Then the use of cooling tower blowdown in a once-through and a recirculating ash sluice system was evaluated. The effects of carbon dioxide mass transfer between the atmosphere and the pond liquor were also determined.

Sodium carbonate softening of 80 percent of the pond recycle water was calculated to be necessary on the assumption that no $CaSO_4 \cdot 2H_2O$ precipitation occurs in the pond and that all of the cooling tower blowdown (towers operating at 15 cycles of concentration) is used as makeup water to the fly ash system. Bottom ash was assumed to be sluiced exclusively with pond water. Gypsum relative saturation in the slurry was found to be 0.998 and in the pond recycle stream before treatment, 0.863. These relative saturations will prevent gypsum scaling in the system as they are below the critical range for scaling of 1.3 to 1.4. Treatment of 80 percent of the recycle liquor corresponds to removing 2.7 g-mole/sec calcium from a 206 ℓ/sec (3270 gpm) stream. Treatment inefficiencies were considered in the calculation.

It was noted that simulations of existing operations indicated that the cycles of concentration may be greatly increased in the cooling towers without scaling with respect to calcium sulfate. However, only limited increases in the cycles of concentration may be implemented before calcium carbonate reaches saturation. Calcium carbonate scaling potential can be controlled with acid treatment of the circulating water.

From the results of various cooling tower and ash sluice system simulations discussed in detail in Reference 29, two alternatives for reducing plant discharges were reported as technically feasible:

a. Cooling tower operation at 5.7 cycles of concentration with acid treatment and once-through ash sluicing with discharge of ash pond overflow after pH adjustment

b. Cooling tower operation at 15.0 cycles with acid treatment and recirculating ash sluice water (Na_2CO_3 softening of 80 percent of pond recycle), with either discharge of the ash pond overflow after pH adjustment or treatment of the overflow with a softening, reverse osmosis, or brine concentration unit and recycle of the clean water as boiler makeup and cooling tower makeup.

The first alternative will require acid treatment in the cooling towers and reaction tanks prior to the fly ash sluice line to minimize $CaCO_3$ and $Mg(OH)_2$ scale formation in the line. Adjustment of the pH of the ash pond overflow may be required, depending on the amount of carbon dioxide mass transfer occurring in the pond. The calculated pH for equilibrium with respect to CO_2 between the pond liquor and the atmosphere is 8.0, whereas the value for no CO_2 transfer is 12.0. This alternative would not allow Bowen to achieve zero discharge without expensive treatment of the ash pond overflow (255 ℓ/sec or 4050 gpm) but would reduce the plant makeup water and discharge rates significantly. The existing ash pond overflow rate for Bowen is about 1600 ℓ/sec (25,000 gpm) by this alternative.

If in the future, SO_2 scrubbers will be installed at Bowen, it was noted that the ash pond overflow could be used as makeup water to the scrubbing system to make use of the available alkalinity from the ash. However, the study did not include evaluating the addition of scrubbers at Bowen, but considered only the cooling and ash handling systems.

Implementation of the second alternative would also require the addition of acid treatment in the cooling towers and reaction tanks in the fly ash sluice system as in the first alternative. Treatment of the ash pond overflow by the lime and soda ash process would reduce the calcium, magnesium, and silica levels, but sulfate concentrations would reach levels high enough for gypsum scaling to occur. In addition, recycle lines and pumps are needed to return a portion of the ash pond liquor for sluicing and sodium carbonate softening of 80 percent of the pond recycle water. Zero discharge may be achieved with this alternative by treatment of the ash pond overflow by a softening, reverse osmosis, brine concentration unit and return of the cleaned water to the boiler and cooling tower makeup systems. Discharge of the ash pond overflow may require pH adjustment as in the first alternative depending on the level of CO_2 transfer in the pond.

It was emphasized in the report (Ref. 29) that neither alternative should be implemented before more information is obtained from bench or pilot scale tests to determine the actual size of reaction tank required in the sluice system, the quantity and frequency of acid wash water required to minimize $CaCO_3$ and $Mg(OH)_2$ scale formation, and the level of gypsum desupersaturation in the pond.

5.6.1.3.4 Economics

The rough cost estimations in 1976 dollars for implementing either of the technically feasible alternatives are summarized. Capital costs as well as operating costs are presented. The assumptions used in calculating these costs are outlined briefly. It is noted (Ref. 29) that these values were only valid for comparative purposes.

The capital costs for the two technically feasible alternatives are \$79,700 and \$920,400, respectively, for alternatives 1 and 2. The fly ash slurry tanks were sized based on a 5-minute residence time of the slurry to allow most of the ash soluble species to be leached in the tank. One tank was used for the fly ash slurry from each unit and was assumed to have one agitator to keep the slurry well mixed.

Pond overflow recycle pumps and piping were sized on the basis of flows calculated in the simulations. Since both alternatives involve sluicing the ash at 10-wt% solids, the tank and agitator costs were identical. The higher capital costs for alternative 2 is the result of the pumps and piping required for recycling a portion of the ash pond liquor and the Na_2CO_3 softening of the pond recycle liquor.

The annual operating costs for the two alternatives are $47, 300 and $243, 400. Three major items were included: acid treatment, power consumption, and softening. Operating the towers at 15.0 cycles of concentration (alternative 2) requires 27 percent more acid than operation at 5.7 cycles (alternative 1). The power consumption for the second alternate is estimated as $66, 700 compared to $2600 for the first. The difference was ascribed to operation of the recycle pumps for the second alternative. A cost of 2 cents/kWh was used to determine power costs.

It is apparent that the first alternative is significantly less expensive than the second. However, zero discharge by eliminating the ash pond overflow discharge is not practical for the first alternative (once-through ash sluicing) because of the high flow rate of 255 ℓ/sec (4050 gpm).

Additional capital and operating costs for treating the 41 ℓ/sec, (650 gpm) ash pond overflow from the second alternative were also presented. The overflow was considered as being treated by a combination of softening, reverse osmosis, and brine concentration, with the clean water recycled to the plant boiler makeup system. The additional capital cost for treatment is about $5.14 million. Therefore, a total capital cost of about $6.06 million was estimated for achieving zero discharge with a recirculating ash sluice system. The additional operating costs were reported as approximately $700, 000 per year with a total of about $942, 000 per year.

5.6.2 Treatment of FGC Waste Streams with Vapor Compression Cycle Evaporation (Resources Conservation Company)

This project is being conducted by Resources Conservation Company (RCC) to demonstrate the practicability of using an RCC brine concentrator as a means of reducing the volume of waste water discharges from FGC processes.

The brine concentrator is a vertical tube, falling-film, vapor compression evaporator that was developed to provide an energy-efficient process for concentrating waste and blowdown waters. The project includes a series of bench and pilot scale tests to demonstrate the feasibility of using the brine concentrator for reducing the waste water volume from FGC processes.

The primary objective of this program is to demonstrate a way to reduce the volume of waste water from a desulfurization process, by evaporative means without scaling heat transfer surfaces, to less than 4 percent of its initial volume and produce a high quality water stream (less than 10-ppm TDS) for recycle back to the power plant.

An appropriate program to demonstrate the feasibility of the brine concentrator for reducing the volume of waste water from FGC processes requires on-site operation of the concentrator at an SO_2 scrubber installation. The Chiyoda "Thoroughbred 101" scrubber installed at the Sholz Power Plant of Gulf Power Company in Sneads, Florida, is planned for the on-site testing because it produces a continuous blowdown stream. The Chiyoda process removes sulfur dioxide from the flue gas by counter-current scrubbing with weak sulfuric acid in a fixed bed absorber. The absorption of SO_2 by H_2O gives sulfurous acid (H_2SO_3), which is catalytically oxidized to H_2SO_4. The concentration of sulfuric acid in the scrubbing liquid is maintained constant by continuous withdrawal to the crystallizer. In the crystallizer, this absorbent is partially neutralized by limestone to produce gypsum. There are two waste streams from the process. One is fly ash bleed from the prescrubber, and the other is the scrubbing liquid bleed from the crystallizer for water balance and control of the chloride concentration in the scrubbing liquor. These two waste streams are combined, neutralized by limestone, and discharged to the liquid waste pond. This combined neutralized waste water stream will be fed to the concentrator during the demonstration tests.

The demonstration program is comprised of the following tasks: (1) evaluation of existing chemical data on waste streams from the Chiyoda process, (2) glassware evaporation tests to confirm predicted precipitation levels and to establish operating conditions for bench model tests, (3) bench model tests (25 gallons per day unit) to verify operating conditions for the on-site demonstration tests, (4) on-site tests with a pilot size (6000 gallons per day) evaporator to demonstrate the vapor compression evaporator's long-term performance in concentrating scrubber waste water, and (5) estimation of the capital and operating costs for a full-scale system.

5.6.3 Power Plant Cooling Tower Blowdown Recycle by Vertical Tube Evaporator with Interface Enhancement

(University of California, Berkeley)

5.6.3.1 Background

Industrial cooling accounts for more industrial water use in the United States than all others combined; about 80 percent of industrial water use is for heat rejection. Much of this use is on a once-through basis, the slightly heated water being returned to the environment. Since the temperature of the rejected coolant is slightly above its previous equilibrium with the environment, proportionately more will evaporate to readjust to equilibrium. This in effect degrades the water quality by concentrating dissolved solids.

The concept of a cooling tower operating with zero discharge is not new; it is, however, more expensive than both once-through cooling and partial evaporation followed by discharge of a somewhat concentrated warm effluent.

Development of a vertical tube foam evaporator (VTFE) promises economic improvements that should make adoption of cooling towers and zero discharge more acceptable to industry (Ref. 30). Improved economy follows from the increased heat transfer performance of VTFE. This permits either a reduction in the heat transfer surface area required or increased steam economy.

The interface-enhanced method of evaporating liquids applied in this study relies on the addition of a few parts per million of a selected surfactant to the liquid to be evaporated, followed by causing the feed liquid to flow as a foamy layer over a heated surface (Ref. 31). As a result of this foamy layer flow, heat transfer from the surface to the feed liquid is augmented by several mechanisms to provide for a significant increase in the rate of evaporation or heat transfer coefficient.

Vertical tube evaporation (VTE) accounts for more industrial evaporation in the United States than all other methods used, and its further improvement by the VTFE method should be of significant value.

In addition, the VTFE process permits the adoption of novel modes of operation previously only marginally feasible; it could also add new capabilities to older VTE applications. One such possible improvement, addressed in this work, is a novel power plant coolant flow that permits the use of waste heat available within conventional coolant flow diagrams to renovate the cooling tower blowdown, producing distilled water for boiler feed, potable use, or recycle as coolant and a dry or slurried salt concentrate. Such an improved coolant flow is diagramed in Figure 53. The work reported here was planned to provide test data and design information for evaluating feasibility of applying this technique to a preexisting power plant. The main objectives of adopting such a flow would be to renovate the cooling tower blowdown at low cost for recycle with zero blowdown, and to utilize a VTFE facility that would interface readily with normal power plant operation. This approach, although as yet unproven, provides the basis for work undertaken in this as well as in a followon project.

5.6.3.2 Results

The results of this work confirm the effectiveness of applying interface enhancement (Ref. 30) to the evaporation of liquids in reducing the energy and capital cost requirements for the renovation and recycle of industrial wastewaters. Interface enhancement, which depends upon foamy two-phase vapor-liquid flow, induced during the evaporation of a liquid flowing over a heat transfer surface, provides a substantial increase in the rate of evaporation of the liquid, after the addition of a selected surfactant. This

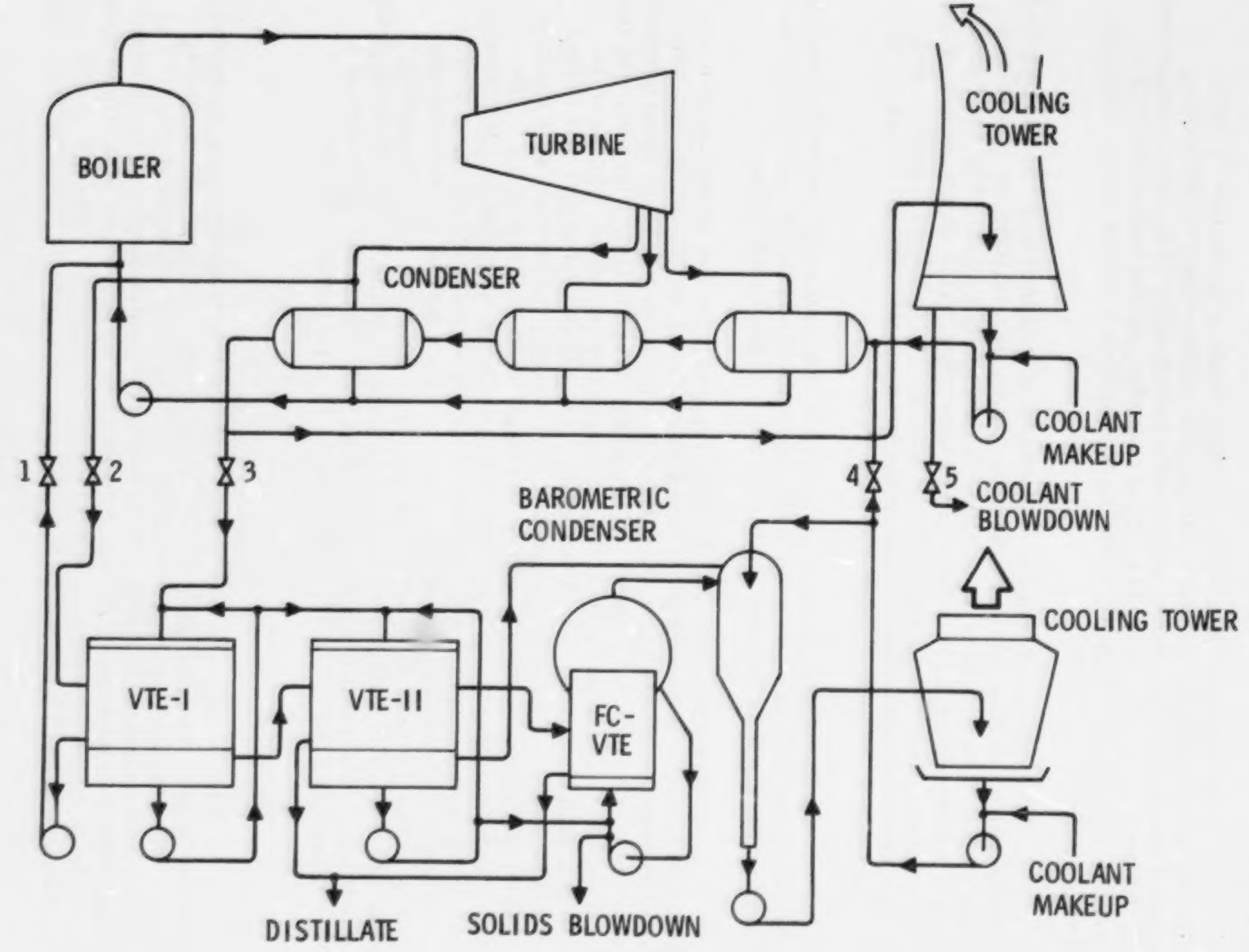

BOILER
TURBINE
CONDENSER
COOLING TOWER
COOLANT MAKEUP
1
2
3
4
5
COOLANT BLOWDOWN
BAROMETRIC CONDENSER
COOLING TOWER
VTE-I
VTE-II
FC-VTE
COOLANT MAKEUP
DISTILLATE
SOLIDS BLOWDOWN

Figure 53. Renovation and recycle of power plant cooling tower blowdown.

project included the construction of two new VTE pilot plants. A two-effect upflow-downflow VTE of 10,000 gallons per day capacity was constructed by adding an identical second effect to an existing single-effect, upflow VTE pilot plant; the second effect was operated in the downflow VTE mode for the work reported here. This pilot plant was used to obtain comparative data on the concentration of saline water by upflow VTE and downflow VTE, and by an interface-enhanced upflow and downflow VTE. These data indicate that while conventional downflow VTE has a higher heat transfer performance than upflow VTE, the interface-enhanced method of upflow VTE operation provides a higher performance than both the interface-enhanced and conventional downflow operations.

A second pilot plant facility assembled for this work was a 5000 gallons per day vertical tube evaporator-crystallizer (EC), tested in the downflow mode. This facility was first used with low-temperature steam heating for crystallizing sodium sulfate and for reducing Mohave power plant cooling tower blowdown to a 30-fold concentrate, at about 125°F. The objectives of these tests were to determine the feasibility of renovating cooling tower blowdown with waste heat available within a conventional power plant cooling cycle; feasibility was indicated by the test results. Secondly, this EC was operated with a vapor compressor (VC) in the evaporation temperature range 215 to 224°F. This series of tests was for the concentration, by both conventional and interface-enhanced modes of operation, of saline agricultural drainage water and industrial cooling tower blowdown. In each of these cases, it was found that the heat transfer performance of the VTE was increased, while its energy requirements were simultaneously reduced, by applying interface enhancement, except in the case of crystallizing sodium sulfate.

5.7 EPA IN-HOUSE RESEARCH

EPA has conducted pilot plant experiments on forced oxidation of FGD scrubber wastes, corresponding to operation with high-sulfur U.S. Eastern coal (Refs. 8 and 32). Primary objectives of the project include complete limestone utilization, maximum oxidation efficiency of calcium sulfite to calcium sulfate, and improved oxidized slurry settling rates. The second and third objectives are related to determining the feasibility of forming usable gypsum as a by-product from the FGD scrubbing process.

In order to assess the characteristics of the gypsum from a utilization standpoint or the suitability of gypsum as a disposal product without the need for further chemical treatment, Aerospace has conducted chemical and physical characterization tests of oxidized wastes formed under conditions equivalent to limestone scrubbing, with and without fly ash.

The laboratory study was completed recently on oxidized samples of filter cake and first- and or second-stage solids which are primarily calcium sulfite. Physical and chemical properties including results of x-ray and SEM analysis are summarized in Section 5.1.1.5.

SECTION VI

UNIVERSITY-RELATED RESEARCH AND DEVELOPMENT

Several universities were identified in the first summary report (Ref. 1) as planning or conducting research and development (R&D) work in the flue gas desulfurization (FGD) waste disposal and utilization area. These included Auburn University, which is conducting FGD waste dewatering experiments under EPA sponsorship (Section 5.2.4), and The Illinois Institute of Technology (IIT), which is studying the applicability of SO_2 from flue gas to form a super phosphate fertilizer. Information not available on the IIT work for this report is expected in the near future.

The University of Louisville is conducting tests to support the EPA study being performed by the Louisville Gas and Electric Co. (LG&E) (Section 5.2.1). Physical characterization data on six FGD scrubber wastes have been reported. The LG&E support includes determination or development of disposal (impoundment) site:

a. Hydrology characteristics

b. Soil permeability

c. Periodic sampling schedule and techniques

d. In-situ strength measurements of the wastes

Laboratory tests on field samples augmenting the field work includes unconfined compression tests and permeability.

The American Society of Testing and Materials (ASTM) soil mechanics tests to characterize the mechanical properties of six wastes have been reported (Ref. 33). These include specific gravity, grain size distributions, plasticity, and compaction. Wastes included samples from LG&E Paddy's Run (mostly calcium sulfite), Southern Services Plant Scholz using the ADL-CEA dual alkali process (about 70/30 sulfite-to-sulfate) Southern Services, Scholz Chiyoda process (mostly gypsum), Kansas City Power and Light La Cygne (waste and fly ash), and two unidentified foreign sludges containing primarily sulfite.

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Triaxial compression tests and a study will be conducted to investigate the effects of various additives on mechanical properties.

Although it is recognized that FGD sludges are not soils and soils engineering experience can only be used to a limited degree in predicting field behavior, some observations were reported. Based on the Unified Soil Classification System (USCS) the Chiyoda and ADL-CEA dual alkali may be classified as silts of low compressibility and Paddy's Run material, as a silt of high compressibility. Other properties are summarized in Table 70.

TABLE 70. SUMMARY OF PHYSICAL PROPERTIES

Source of Waste	Specific Gravity[a]	Grain Size Fractions[b]			Moisture-Density Relationship	
		Sand-Size (>0.074 mm)	Silt-Size (0.002 to 0.074 mm)	Clay-Size (<0.002 mm)	Maximum Dry Density, pcf	Water Content, %
LG&E Paddy's Run	2.49	0%	97%	3%	84.0	31.3
Gulf Power, Scholz Chiyoda	2.35	18	76	6	94.8	13.3
Gulf Power, Scholz ADL-CEA	2.56	4	93	3	85.3	26.8
Kansas City Power La Cygne	-	-	-	-	102.4	17.1
LG&E Paddy's Run with 50% Fly Ash	-	-	-	-	91.5	25.0

[a] 70° C.

[b] ASTM D422.

SECTION VII

INDUSTRIAL RESEARCH AND DEVELOPMENT AND OPERATIONAL APPLICATIONS

This section supplements the information reported in Ref. on the work being performed by various industrial organizations and other governmental agencies in their treatment of flue gas desulfurization (FGD) wastes. The operational applications of FGD treatment and disposal in the United States are also summarized.

7.1 RESEARCH AND DEVELOPMENT

7.1.1 Electric Power Research Institute (EPRI)

In December 1976, a project was initiated by EPRI, "By Product/Wastes Disposal for Flue Gas Cleaning Processes" (Ref. 34). Its objectives are (1) to develop and maintain a data base on sludge and task handling procedures, (2) to provide an independent evaluation of sludge fixation processes, (3) to quantify variables affecting the solubility of trace elements, (4) to establish guidelines for disposal, and (5) to evaluate sludge dewatering processes and hardware. Michael Baker Corporation and Radian Corporation are the contractors involved in the task evaluation. Envirotech is conducting the dewatering task.

7.1.2 New York State Energy Research and Development Authority (NYSERDA)

A study to investigate the feasibility of using chemically treated flue gas scrubber waste as artificial fishing reefs was initiated by NYSERDA (Ref. 35). The research contract was awarded to the Marine Sciences Research Center of the State University of New York at Stony Brook.

7.1.3 Southern Services

Recent testing of the Chiyoda process the Southern Services Plant Scholz, Chattahoochee, Florida, has been directed toward a water saving approach to reduce usage by a factor of two (Ref. 36). Testing was scheduled to continue through December 1976. In addition, 3000 4 × 12 ft sheets of wallboard were produced for evaluation using a 50/50 blend of natural gypsum and gypsum produced by the Chiyoda process.

7.2 UTILITY POWER PLANT APPLICATIONS

Full-scale experience and future plans relating to FGD chemical treatment and disposal by utilities are summarized in Tables 71 and 72. A total of 15 plants, representing 9 utilities totaling 7484 MWe, are currently committed to initiate by 1979 the chemical treatment of lime-limestone scrubber wastes prior to disposal. Five stations (2100 MWe) are now in operation; seven others (3959 MWe) will start up by the end of 1977, and three others have made definite commitments to begin by 1979. Also, 16 plants representing 3646 MWe are identified as scrubbing and disposing untreated lime-limestone scrubbed FGC wastes in lined or in natural clay unlined ponds in 1976 (Ref. 2).

Experience with a limestone wet scrubber, gypsum-producing system operating on Unit 1 at the Northern States Power Company Sherbourne generating plant was described recently (Ref. 9). Unit 1 (700 MWe) became operational in May 1976. The plant burns Montana subbituminous coal (8300 Btu/lb 0.8 percent S and 9.0 percent ash). The scrubber is a two-stage venturi and marble bed scrubber. Fifty percent of the SO_2 and 99 percent of the particulate matter in the flue gas are removed.

The sulfite slurry from the scrubber is air oxidized in a reaction tank. The calcium sulfate slurry is withdrawn at 10 percent total solids. The gypsum slurry is thickened and pumped to the fly ash pond. Thickener overflow is returned to the scrubber recirculation tank where it is used as makeup water in the scrubber system. The slurry in the fly ash pond is allowed to settle, and the supernate is also returned to the scrubber recirculation tank.

Unit 2 (700 MWe) is scheduled to begin operation in May 1977.

TABLE 71. FGC CHEMICAL TREATMENT PROCESSES: UTILITY PLANT CHARACTERISTICS

Utility	Power Station	Station Size, MW	Coal Characteristics			FGD Absorbent	FGD Installation	FGD Startup	Scrubber Size, MW	Particulate Control Device Upstream of Scrubbers	Scrubber System	By-pass	Ref. in First R & D Report[a]	Ref. This Report
			% S	% Ash	Btu/lb									
Commonwealth Edison	Will County, Unit No. 1	167	4	10	9,500	Limestone	Retrofit	Feb 1972	167	ESP used only when FGD not in use	Two venturi and countercurrent tray absorber modules; Babcock & Wilcox (B & W)	Yes	28, 31	2
Duquesne Light Co.	Phillips	410	1.0 to 2.8	18	11,300	Slaked lime	Retrofit	Jul 1973	410	Mechanical cyclones followed by ESP, Research-Cottrell; venturis	One 2-stage variable throat venturi module processing 125 MW; four single-stage modules processing remainder; Chemico	Yes	28, 32	2
Duquesne Light Co.	Elrama	510	1.0 to 2.8	18	12,000	Hydrated lime with switch to quicklime as soon as possible	Retrofit	Nov 1975	510	Mechanical cyclones followed by ESP; venturis	Five single-stage venturis; Chemico	Yes	28, 33, 34	2, 37
Southern California Edison (SCE)	Mohave, Unit No. 1	790	0.5 to 0.8	10	11,500	Limestone (lime alternative)	Retrofit	Jan 1974	170	ESP, Research-Cottrell	Vertical TCA module; Universal Oil Products (UOP); test completed Jul 1975	Yes	28, 35, 36	
	Mohave, Unit No. 2	790	0.5 to 0.8	10	11,500	Lime (limestone alternative)	Retrofit	Nov 1973	170	ESP, Research-Cottrell	Horizontal 4-stage counter-current module; SCE; tests completed Feb 1975; 170-MW prototype unit to Public Service Corners Station	Yes	28, 35, 36	
Central Area Power Coordination (CAPCO) Group Ohio Edison Co. Duquesne Light Co. Cleveland Electric Co. Toledo Edison Co. Pennsylvania Power Co. (operator)	Bruce Mansfield, Unit No. 1	835	4 to 5	12.5	11,900	Lime	New	Apr 1976	835	None	2-stage scrubbers; Chemico		28, 37, 38	2
	Unit No. 2	835	4 to 5	12.5	11,900	Lime	New	Apr 1977	835	None	2-stage scrubbers; Chemico		28, 37, 38	2

TABLE 71. FGC CHEMICAL TREATMENT PROCESSES: UTILITY PLANT CHARACTERISTICS (Continued)

Utility	Power Station	Station Size, MW	Coal Characteristics			FGD Absorbent	FGD Installation	FGD Startup	Scrubber Size, MW	Particulate Control Device Upstream of Scrubbers	Scrubber System	By-pass	Ref. in First R & D Report[a]	Ref. This Report
			% S	% Ash	Btu/lb									
Louisville Gas and Electric Co. (LG&E)	Paddy's Run, Unit No. 6	65	3.5 to 4.0	13	11,500	Carbide lime	Retrofit	Apr 1973	65	ESP	Combustion Engineering Marble Bed			2
	Cane Run, Unit No. 4	178	3.5 to 4.0	11 to 12	11,500	Lime	Retrofit	Aug 1976	178	ESP	American Air Filter	Yes	28	2
	Cane Run, Unit No. 5	183	3.5 to 4.0			Lime	Retrofit	Dec 1977	183		Combustion Engineering		28	
	Mill Creek, Unit No. 3	425	3.5 to 4.0			Lime	New	Jul 1977	425		American Air Filter		28	
Columbus and Southern Ohio Electric	Conesville, Unit No. 5	400	4.5 to 4.9	17		Thiosorbic lime	New	Jan 1977	400	ESP	UOP		28	
	Conesville, Unit No. 6	400	4.5 to 4.9	17		Thiosorbic lime	New	Jan 1978	400	ESP	UOP		28	
Indianapolis Power and Light	Petersburg, Unit No. 3	530	3.0 to 3.5	15		Limestone	New	Sep 1977	530	ESP	4 modules; UOP		28	2
Allegheny Power System	Pleasants, Unit No. 1	625	4.5			Thiosorbic lime	New	Mar 1979	625	ESP	B & W			2
Utah Power & Light Co.	Emery, Unit No. 1	415	0.5			Lime	New	Jun 1978	415	ESP	Chemico	Yes		2
Texas Utilities Co.	Martin Lake, Unit No. 1	793	1.0			Limestone	New	Jan 1977	793	ESP	Research-Cottrell			2
	Martin Lake, Unit No. 2	793	1.0			Limestone	New	Oct 1977	793	ESP				

[a] Reference 1.

TABLE 72. FGC WASTE TREATMENT AND DISPOSAL STATUS

Utility	Power Station	FGC Waste Treatment Processing				FGC Waste Disposal			Ref. in First R&D Report[a]	Ref. This Report
		Process	Treatment Material	Waste Solids Content	Treatment Conditions	Interim Storage	Transport Mode	Final Disposal Site		
Commonwealth Edison	Will County, Unit No. 1 (167 MW)	Own with Chicago fly ash	Lime and fly ash	35 to 45% clarifier underflow	10% lime and 20% fly ash (of dry sludge solids)	7-acre onsite clay-lined disposal basin (prior to Sep 1975)	Rotary mix concrete truck	Offsite to permanent clay-lined landfill disposal site operated by Material Service Co. since Sep 1975	29, 31	2
Duquesne Light Co.	Phillips (410 MW)	Calcilox®	Calcilox®	30 to 40% clarifier underflow	10% on dry sludge basis	Three curing ponds 6000 yd^3, each with 10 to 14-day capacity	Dumptruck	~1 mi from plant; 2-yr capacity; treated waste solidifies in place	22, 32	2
		IU Conversion Systems, Inc. (IUCS) estimated startup date: Oct. 1977		30 to 40% clarifier underflow, filtered to approx. 60% solids						38
Duquesne Light Co.	Elrama (510 MW)	IUCS, permanent plant estimated startup date: Nov 1977	Lime and fly ash	35 to 40% clarifier underflow, filtered to 50 to 60% solids before treatment	Treating waste produced by 210 MW equivalent, using equipment from Mohave site tests	None	Truck, 25-ton capacity	Landfill ~2 mi from plant	22, 33, 39	2, 37, 38
SCE	Mohave, Unit No. 1	IUCS			Treated all sludge from 167-MW system for 1 yr			Landfill of 25,000 tons for housing, parking lot construction, streets and roads in Bullhead City and Riviera; synthetic aggregate manufacture	25, 29, 35, 36	
	Mohave, Unit No. 2	Dravo	Calcilox®					Unlined pond	25	
CAPCO Group	Bruce Mansfield, Unit No. 1 (825 MW)	Dravo	Calcilox®	30% solids clarifier underflow		None	Treated waste pumped to disposal site ~7 mi; pond supernate returned for reuse	400-ft high embankment dams a 1330-acre valley	22, 37, 38	
Ohio Edison Co. Duquesne Light Co. Cleveland Electric Co. Toledo Edison Co. Pennsylvania Power Co. (operator)	Unit No. 2 (825 MW)							Site estimated to be adequate for 20 to 25 yr		

TABLE 72. FGC WASTE TREATMENT AND DISPOSAL STATUS (Continued)

Utility	Power Station	FGC Waste Treatment Processing				FGC Waste Disposal			Ref. in First R&D Report[a]	Ref. This Report
		Process	Treatment Material	Waste Solids Content	Treatment Conditions	Interim Storage	Transport Mode	Final Disposal Site		
LG&E	Paddy's Run, Unit No. 6 (65 MW)	LG&E	Carbide lime; fly ash mixed at disposal site	22 to 24% solids in clarifier underflow, filtered to 35 to 45% solids	3 to 5% additive (dry sludge basis) added in thickener	None	Truck 1 mi at $0.50/ton	10-acre borrow pit, depth 20 to 30 ft	40	2
	Cane Run, Unit No. 4 (178 MW)	LG&E	Fly ash						22, 29	2
	Mill Creek, Unit No. 3 (425 MW)	LG&E							22, 29	
Columbus and Southern Ohio Electric Co.	Conesville, Unit No. 5 (400 MW)	IUCS	Lime	Thickener underflow at 30% solid, secondary thickening then vacuum filtered	Treatment plant completed May 1976; expect to start processing waste in Feb 1977; blend with dry fly ash	None	Disposal site 1/3 mi from plant; treatment plant midway; conveyor from treatment plant to disposal site	75-acre (minimum) landfill, 18 to 20 years at site	25, 29 41, 42	38
	Conesville, Unit No. 6 (400 MW)	IUCS	Lime							
Indianapolis Power and Light	Petersburg, Unit No. 3 (530 MW)	IUCS						Landfill	29	39
Allegheny Power System	Pleasants, Unit No. 1 (625 MW)	Dravo	Calcilox®							
Utah Power and Light Co.	Emery, Unit No. 1 (400 MW)		Fly ash							2
Texas Utilities Co.	Martin Lake, Unit No. 1 (793 MW)	R-C								
	Martin Lake, Unit No. 2 (793 MW)	R-C								

[a] Reference 1.

SECTION VIII

FOREIGN TECHNOLOGY

Significant published information subsequent to that provided in References 1 and 37 was not available during this reporting period. It is noted that cost estimates for the production of gypsum by the Chiyoda, Dowa, and Kureha processes as applied to U.S. conditions are being calculated by the Tennessee Valley Authority (TVA) and is expected to be published in the next report (Section 5.3.2).

A summary of the major characteristics of the various Japanese gypsum producing processes (Ref. 40) are summarized in Table 73.

TABLE 73. GYPSUM-PRODUCING PROCESSES BASED ON WET LIME-LIMESTONE SCRUBBING

Process / Features	Mitsubishi-JECCO	Mitsui-Miike	Babcock Hitachi	Chubu-Mkk (CM Process)	Kobe Steel (CAL Process)	Sumitomo-Fuji Kasui (Moretana Process)	IHI-TCA	Chemico-IHI	Kawasaki	Tsuki-shima (TSK Process)	Nippon Kokan
Electrostatic Precipitator (ESP)	None	None	None	None	None	Yes	No	Yes	None	NAV[a]	-[b]
Range of Inlet SO_2, ppm	550 - 20,000	1500 - 2350	400 - 1500	NAV	200 - 400	800	1300	NAV	NAV	NAV	NAV
Exhaust Gas Cooler, type	Tower	None	Venturi	Spray	Yes	Yes	Yes	None	Yes	NAV	-[b]
Scrubber/Absorber, type	Grid, packed	Venturi	Perforated plate	Screen	NAV	Perforated plate	TCA	Venturi	NAV	Bahco	Spray tower
Absorbent	Lime or $CaCO_3$	$CaCO_3$	$CaCO_3$	$CaCO_3$	Lime with $CaCl_2$ added	Lime	Lime	$CaCO_3$	Lime/$Mg(OH)_2$ $CaCO_3$/Mg $(OH)_2$	Lime	Lime
No. of Absorbers	1 or 2	2	1	1	1	1	2	2	NAV	NAV	-[b]
pH Adjusted, with	6 - 7, H_2SO_4	6, Flue gas	6, H_2SO_4	6, H_2SO_4	7, None	6, H_2SO_4	NAV, Yes	NAV, H_2SO_4	NAV, H_2SO_4	NAV	-[b]
SO_2 Removal Efficiency, %	90 - 97	NAV	90	90	90	90 - 97	90	80	NAV	NAV	-[b]
Oxidizer	Tower, rotary atomizer, air	Tower, air	Rotary atomizer, air	Rotary atomizer, air	Air	Air	Air	Air	Air	NAV	-[b]
Gypsum Dewatering	Thickener and centrifuge	Thickener and centrifuge	Thickener and centrifuge	Thickener and centrifuge	Centrifuge	Centrifuge	NAV	Thickener and centrifuge	Thickener and centrifuge	NAV	-[b]
Gypsum Moisture Content, %	8 - 10	10 - 15	7 - 8	10 - 12	10% (0.5%$CaCl_2$)	10 - 12	10 - 15	NAV	NAV, 0.5% $MgSO_4$	NAV	-[b]
Power Plants, in Operation, MWe	31, 5730	5, 856	5, 1075	2, 102	2, 240	8, 258	3, 210	2, 530	3, 187	1, 20	1, 38
Cost: Capital Operating	\$60/kW, NAV	NAV	NAV	NAV	NAV	\$60/kW, NAV	NAV	NAV	NAV	NAV	-[b]
Gypsum/Use	High quality wallboard, cement	Usable for wallboard, cement	Saleable	Wallboard	Cement retarder	Wallboard, cement	NAV	Not saleable, excessive fly ash content	Cement retarder	NAV	-[b]

[a] Not available.

[b] Similar to Mitsubishi - JECCO process.

TABLE 73. GYPSUM-PRODUCING PROCESSES BASED ON WET LIME-LIMESTONE SCRUBBING (Continued)

Features / Process	Showa Denko	Kureha-Kawasaki	Nippon Kokan	Chiyoda	Dowa	Kurabo	Tsukishima	Hitachi-Tokoyo Electric
Electrostatic Precipitator (ESP)	None	Yes	Yes	None	None	None	None	Yes
Range of Inlet SO_2, ppm	NAV[a]	600 - 1300	250 - 500	600 - 1500	400 - 1700	NAV	750 - 1300	NAV
Exhaust Gas Cooler, type	No	Venturi type	Spray tower	Yes	No	Yes	No	NAV
Scrubber, type	Vertical cone	Packed grid type	Screens	Packed tower	Packed Tower	KBCA	NAV	NAV
pH	7	7	6	NAV	3 - 4	<4	NAV	NAV
Absorbent/Precipitant	$Na_2SO_3/CaCO_3$	$Na_2SO_3/CaCO_3$	$(NH_4)_2SO_3/Ca(OH)_2$	$H_2SO_4(Fe^{+3})/CaCO_3$	$AL_2(SO_4)_3/CaCO_3$	$(NH_4)_2SO_4/Ca(OH)_2$	$Na_2SO_3/Ca(OH)_2$	Carbon
No. of Absorbers	4	1	1 (5 stages)	1	1	NAV	NAV	$CaCO_3$
SO_2 Removal Efficiency, %	95	~97	95	>90	95	~90	NAV	80 - 90
Oxidizer	Air	Air	Air	Air	Air	Air	Air	$CaCO_3$ reacting with dil. H_2SO_4
Oxidation Stages, number	NAV	NAV	2	1 (oxidized in absorber)	1	1	NAV	NAV
pH, adjusted with	NAV, H_2SO_4	NAV, H_2SO_4	4, H_2SO_4	--	--	4	NAV	NAV
Gypsum Dewatering	Centrifuge	Centrifuge	Centrifuge	Centrifuge	Centrifuge	Centrifuge	Thickener, filter	Centrifuge
Gypsum Moisture Content, %	~9 with ~300 ppmNa^+	< 8%	NAV	6 - 10	NAV	9	NAV	10 - 12
Plants in Operation, MWe	16, 785	6, 1900	1, 46	13, 1390	2, 90	4, 129	4, 228	1, 150
Cost: Capital Operating	\$43/kW(1973) 4 mills/kWh	\$50/kW(1973) NAV	Available	\$65 - 70 kW(1973)	\$55/kW(1973)	Available	NAV	NAV
Gypsum/Use	Wallboard	Good quality gypsum	Good quality gypsum	Good quality gypsum	Wallboard, cement, 0.05% Al	Saleable	NAV	NAV

[a] Not available.

REFERENCES

1. P. P. Leo and J. Rossoff, Control of Waste and Water Pollution from Power Plant Flue Gas Cleaning Systems: First Annual R&D Report, EPA-600/7-76-018, U.S. Environmental Protection Agency, Research Triangle Park, NC (October 1976).

2. Summary Report - Flue Gas Desulfurization Systems, prepared by PEDCO-Environmental Specialists, Inc., for the U.S. Environmental Protection Agency, Research Triangle Park, NC, Contract No. 68-02-1321 (September-October 1976).

3. J. Rossoff, et al., Disposal of By-Products From Nonregenerable Flue Gas Desulfurization Systems: Second Progress Report, EPA-600/7-77-052, U.S. Environmental Protection Agency, Research Triangle Park, NC (May 1977).

4. J. L. Mahloch, D. E. Averett, and M. J. Bartos, Jr., Pollutant Potential of Raw and Chemically Fixed Hazardous Industrial Wastes and Flue Gas Desulfurization Sludges: Interim Report, EPA-600/2-76-182, U.S. Environmental Protection Agency, Cincinnati, OH (July 1976).

5. R. B. Fling, et al., Disposal of Flue Gas Cleaning Wastes: EPA Shawnee Field Evaluation: Initial Report, EPA-600/2-76-070, U.S. Environmental Protection Agency, Research Triangle Park, NC (March 1976).

6. J. Rossoff, et al., Disposal of By-Products from Nonregenerable Flue Gas Desulfurization Systems: Final Report, Prepared by The Aerospace Corporation for the U.S. Environmental Protection Agency, Research Triangle Park, NC, Contract No. 68-02-1010 (to be published).

7. R. B. Fling, et al., Disposal of Flue Gas Cleaning Wastes: EPA Shawnee Field Evaluation: Second Annual Report, EPA-600/7-78-024, U.S. Environmental Protection Agency, Research Triangle Park, NC (February 1978).

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8. R. H. Borgwardt, "IERL-RTP Scrubber Studies Related to Forced Oxidation," paper presented at the U.S. Environmental Protection Agency, Symposium on Flue Gas Desulfurization, New Orleans, March 8-11, 1976.

9. R. J. Kruger, [illegible]. A. Noer, and T. M. Pryslak, "Sherbourne County Wet Scrubber System Experience," Paper presented at the Sulfur Removal Systems Conference, University of Wisconsin, Madison, WI, January 6-7, 1977.

10. P. P. Leo and J. Rossoff, *Controlling SO_2 Emissions from Coal-Fired Steam-Electric Generators: Solid Waste Impact*, Vol. II, EPA-600/7-78-044b, U.S. Environmental Protection Agency, Research Triangle Park, NC (March 1978).

11. J. Rossoff and R. C. Rossi, *Disposal of By-Products from Non-Regenerable Flue Gas Desulfurization Systems: Initial Report*, EPA-650/2-74-037-a (NTIS No. PB 237-114/AS), U.S. Environmental Protection Agency, Research Triangle Park, NC (May 1974).

12. H. G. Blecker and T. M. Nichols, *Capital and Operating Costs of Pollution Control Equipment Modules, Vol. II, Data Manual*, EPA-R5-73-023b, U.S. Environmental Protection Agency, Washington, DC (July 1973).

13. J. W. Jones, J. Rossoff, and R. C. Rossi, "Flue Gas Cleaning Waste Characterization and Disposal Evaluation," *Proceedings: Fourth International Ash Utilization Symposium – St. Louis, March 1976*, U.S. Environmental Protection Agency, Research Triangle Park, NC (March 1976).

14. J. L. Mahloch, "Chemical Properties and Leachate Characteristics of FGD Sludges," Paper presented at the AICHE Symposium, Atlantic City, NJ, August 29 - 1 September 1976.

15. J. L. Mahloch, "Chemical Fixation of FGD Sludges: Physical and Chemical Properties," Paper presented at the U.S. Environmental Protection Agency Symposium on Flue Gas Desulfurization, New Orleans, March 8-11, 1976.

16. J. Rossoff, et al., "Disposal of By-Products from Non-Regenerable Flue Gas Desulfurization Systems: A Status Report," *Proceedings: Symposium on Flue Gas Desulfurization – Atlanta, November 1974, Volume I*, EPA-650/2-74-126-a (NTIS No. PB 242-572/AS), U.S. Environmental Protection Agency, Research Triangle Park, NC (December 1974).

17. H. R. Borgwardt, "Limestone Scrubbing of SO_2 at EPA Pilot Plant," Progress Report, June 11, 1973.

18. Grob, et al., *American Laboratory*, *1* (6), 13-25 (1975).

19. Taylor, *Combustion*, *45* (4), 15-22 (1973).

20. Schropfev, Zeitschrift fur Anorg. und Allg. Chemie, 401 (1), 1-14 (1973).

21. P. A. Corrigan, Preliminary Feasibility Study of Calcium-Sulfur Sludge Utilization in the Wallboard Industry, TVA S-466, Tennessee Valley Authority, Muscle Shoals, AL (June 21, 1974).

22. J. I. Bucy, J. L. Nevins, and P. A. Corrigan, "Potential Utilization of Controlled SO_x Emissions from Power Plants in the Eastern United States," Paper presented at the U.S. Environmental Protection Agency Symposium on Flue Gas Desulfurization, New Orleans, March 8-11, 1976.

23. "An Evaluation of the Disposal of Flue Gas Desulfurization Wastes in Mines and the Ocean -- Initial Assessment," prepared by Arthur D. Little, Inc., Cambridge, MA for the U.S. Environmental Protection Agency, Research Triangle Park, NC, Contract No. 68-02-2334 (to be published).

24. F. J. Cservenyak, Recovery of Alumina from Kaolin by the Lime-Soda Sinter Process, R. I. 4069, U.S. Dept. of the Interior, Bureau of Mines, College Park, MD (1947).

25. F. A. Peters, P. W. Johnson, J. J. Henn, and D. C. Kirby, Methods for Producing Alumina from Clay, R. I. 6927, U.S. Dept. of the Interior, Bureau of Mines, College Park, MD (1966).

26. Proposal for the Development of a New Process for the Economic Utilization of the Solid Waste Effluent from Linestone Slurry Wet Scrubber Systems, Vols. I and II, Proposal No. 27359.000, TRW Systems Group, Inc., Redondo Beach, CA (1974).

27. O. W. Hargrove and J. G. Noblett, "Water Recycle/Reuse Alternatives at the Arizona Public Service Four Corners Station," Radian Technical Note 200-118-07, EPA Contract 68-03-2339, July 23, 1976.

28. W. Gathman and J. G. Noblett, "Water Recycle/Reuse Alternatives at the Public Service of Colorado Comanche Plant," Radian Technical Note 200-118-09, EPA Contract 68-03-2339, August 23, 1976.

29. J. G. Noblett, "Water Recycle/Reuse Alternatives at the Georgia Power Company Plant Bowen," Radian Technical Note 200-118-08, EPA Contract 68-03-2339, August 17, 1976.

30. Renovation of Power Plant Cooling Tower Blowdown for Recycle by Evaporation: Crystallization with Interface Enhancement, University of California, Berkeley, CA, EPA Grant No. R803-257-012-3 (to be published).

31. U.S. Patent No. 3,846,254, November 5, 1974, and foreign counterpart patents.

32. R. H. Borgwardt, "Pilot Evaluation of Methods of Increasing Limestone Utilization in FGD Scrubbers," Paper presented at the Sixty-Eighth Annual Meeting of the American Institute of Chemical Engineers, Los Angeles, November 16-20, 1975.

33. D. J. Hagerty, Summary: Status of FGD Sludge Testing Program, University of Louisville, Department of Civil Engineering, Louisville, KY (November 1976).

34. K. B. Andrews, Research and Development Projects, Electric Power Research Institute (November 4, 1976).

35. Coal Waste Disposal at Sea, Information pamphlet, New York State Energy Research and Development Authority, NY.

36. Personal communication: R. Edwards, Southern Services, to P. P. Leo, The Aerospace Corporation, September 16, 1976.

37. Personal Communication: R. Patton, IU Conversion Systems, to J. Rossoff, The Aerospace Corporation, April 28, 1976.

38. Personal Communication: H. Mullen, IU Conversion Systems, to J. W. Jones, Environmental Protection Agency, January 17, 1977.

39. Personal Communication: R. J. Bacskai, IU Conversion Systems, to P. P. Leo, The Aerospace Corporation, January 17, 1977.

40. J. Ando and G. A. Isaacs, SO_2 Abatement for Stationary Sources in Japan, EPA-600/2-76-013-a, U.S. Environmental Protection Agency, Research Triangle Park, NC (January 1976).